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INVESTIGATION OF NEHRP/IBC SIMPLIFIED SEISMIC DESIGN PROCEDURES FOR NON-TRADITIONAL SITE CONDITIONS

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ABSTRACT

Current NEHRP/IBC guidelines for simplified seismic design are based mainly on experience and data from sites in the Western U.S. The unique geological and geotechnical conditions prevalent in the Central and Eastern U.S. (CEUS) may not be captured adequately by current guidelines. For instance, areas where abrupt velocity contrasts caused by very hard rock (V_s > 3000 m/s) close to the ground surface are prevalent in the central and eastern US. This geologic condition causes significant amplifications at short structural periods that produce motions well above those typically predicted by current NEHRP/IBC procedures based on the average shear wave velocity of the top 30 m (100 ft) of the profile. Also, the common CEUS geological condition such as the Atlantic Coastal Plain, which consists of a stack of unconsolidated sediments up to 1000 meters thick along the coast, produce an amplification of ground motions at long periods (typically > 2 seconds) that greatly exceeds the NEHRP/IBC simplified spectra—current guidelines are unconservative for these conditions. Conversely, the thick sediment wedge filters high frequency motions and produces a significant reduction of the ground motions at shorter periods. The resulting ground motions at periods less than 1.0 second could be far below the simplified guidelines. This study presents the findings from the site response analyses that account for these types of unique geologic conditions.

TABLE OF CONTENTS

ABSTRACT 2
TABLE OF CONTENTS 3
1. INTRODUCTION 4
2. COLUMBIA, SOUTH CAROLINA 10
3. CHARLESTON, SOUTH CAROLINA 22
4. SUMMARY AND CONCLUSIONS 35
REFERENCES 37

1. INTRODUCTION

The National Earthquake Hazard Reduction Program (NEHRP) site classifications and amplification factors are biased to Western United States (WUS) seismic experience. The NEHRP seismic procedures were developed with generic central and eastern United States geologic conditions. Unique geologic conditions in the CEUS introduce site conditions which are not accounted for by the NEHRP provisions. Specifically, very hard rock near the ground surface, impedances between soil layers and deep sediment stacks are not modeled with the simplified NEHRP procedures.

The NEHRP generalized seismic hazard maps are developed from CEUS attenuation relationships and a generic geologic profile transitioning from hard rock to the "B-C Boundary" described in detail by Frankel et al. (1996, 2000 and 2002) and Petersen et al. (2008) . Figure 1-1 shows the shear wave velocity versus depth profile used to develop the NEHRP hazard maps. The shear wave velocities transition from over 3300 m/sec at a depth of 2000 m to 762 m/sec at the "B-C Boundary". Generalized seismic hazard maps were developed for use in the NEHRP site response model accounting for CEUS attenuation behavior using this profile and information from historical and small CEUS earthquakes in the region. Figure 1-2 shows generalized seismic hazard maps for 0.2 sec and 1.0 sec spectral acceleration (*SA*) ordinates as a percentage of gravity (g); the contours of color indicate different levels of shaking. The generalized maps are provided for multiple spectral acceleration ordinates for use in developing response spectra for structural design on the United States Geological Survey (USGS) website: earthquake.usgs.gov/hazards/. Using NEHRP site classification and site amplification factors these values are modified for site specific soil conditions in the upper 30 m (V_{S30}) using standard geotechnical investigation tools such as the Standard Penetration Test (SPT), Cone Penetration Test (CPT), and a variety of shear wave velocity instruments.

Geologic conditions unique to the CEUS include very hard rock, impedances, and deep sediment stacks. Hard rock found in the CEUS is typically greater than 2500 m/sec. The hard rock is often close to the ground surface which can create impedances or jumps in the stiffness between the rock and overlying materials. Impedances are found throughout the complex and vast CEUS geologic matrix; these stiffness jumps modify motions and can occur at various levels within the geologic profiling. Complex erosional and depositional processes throughout the region provide a broad range in sediment thickness over relatively short distances in the CEUS. The thickness and stiffness of these deposits can significantly modify hard rock motions. The current computation of the V_{s30} parameter does not account for these unique jumps in the stiffness.

Figure 1-3 provides a geologic map of the CEUS highlighting locations of impedances (black ovals) and deep stacks (white ovals). Impedances generally occur in all areas of the CEUS; their locations within the geologic profile vary across the region on a large and small scale. Deep sediment stacks are generally found in the Coastal Plain geologic province and the Mississippi Embayment. Wedges of sediment range from a few to over 1000 m in thickness within these areas. Outside of these significant deep stacks, the complex river systems across the region provide a range of site specific conditions.

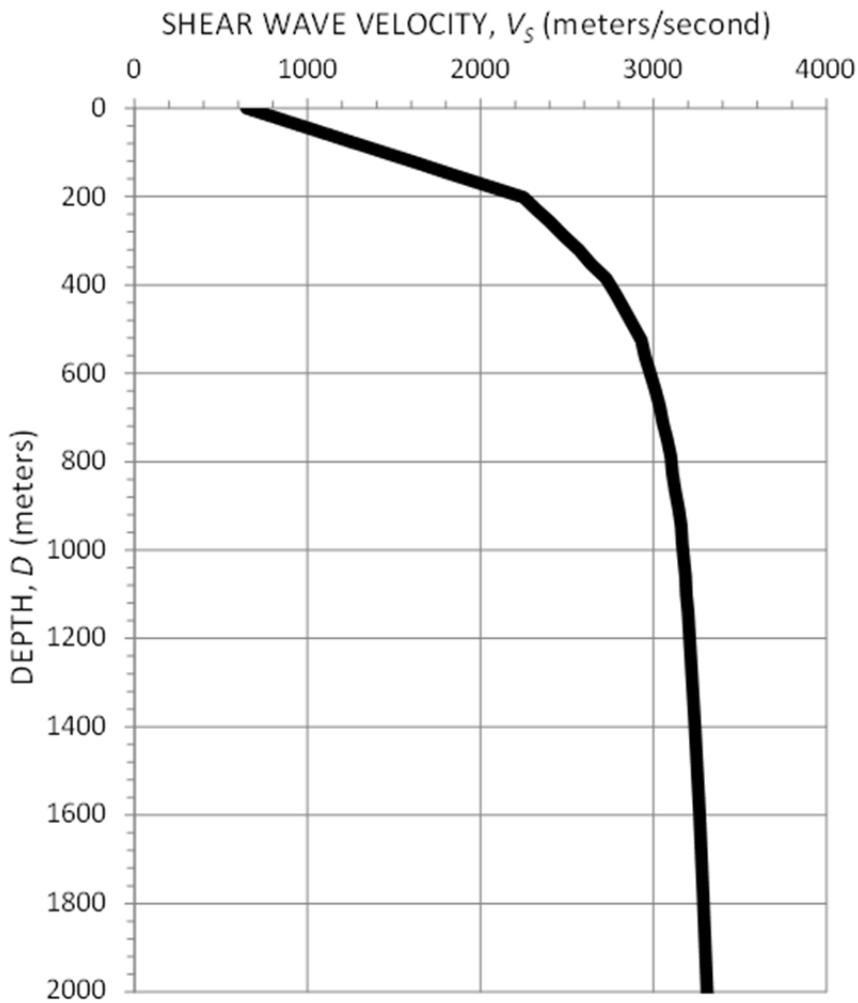

Figure 1-1. Generic geologic profile used for development of the generalized NEHRP seismic hazard maps.

Site specific studies accounting for CEUS geologic conditions lead to different site response behavior and resulting site amplification factors as compared to the NEHRP simplified procedures. Preliminary site response analyses of Fall Line sites and those in the Coastal Plain geologic provinces of the CEUS are presented and compared to the NEHRP simplified model and observations of the 1886 Charleston, SC (M_w7.3) Earthquake. Sites in Columbia and Charleston, South Carolina are used as examples to illustrate the effect of impedances and deep stacks on site response behavior in the CEUS. Site amplification factors and response spectra computed from site specific studies are compared to NEHRP values. The depth to impedances and the magnitude/transition of the impedances are very important for predicting site response behavior in the CEUS. The site specific studies show how current interpretations of the code can lead to wrong answers when performing site response studies in the CEUS.

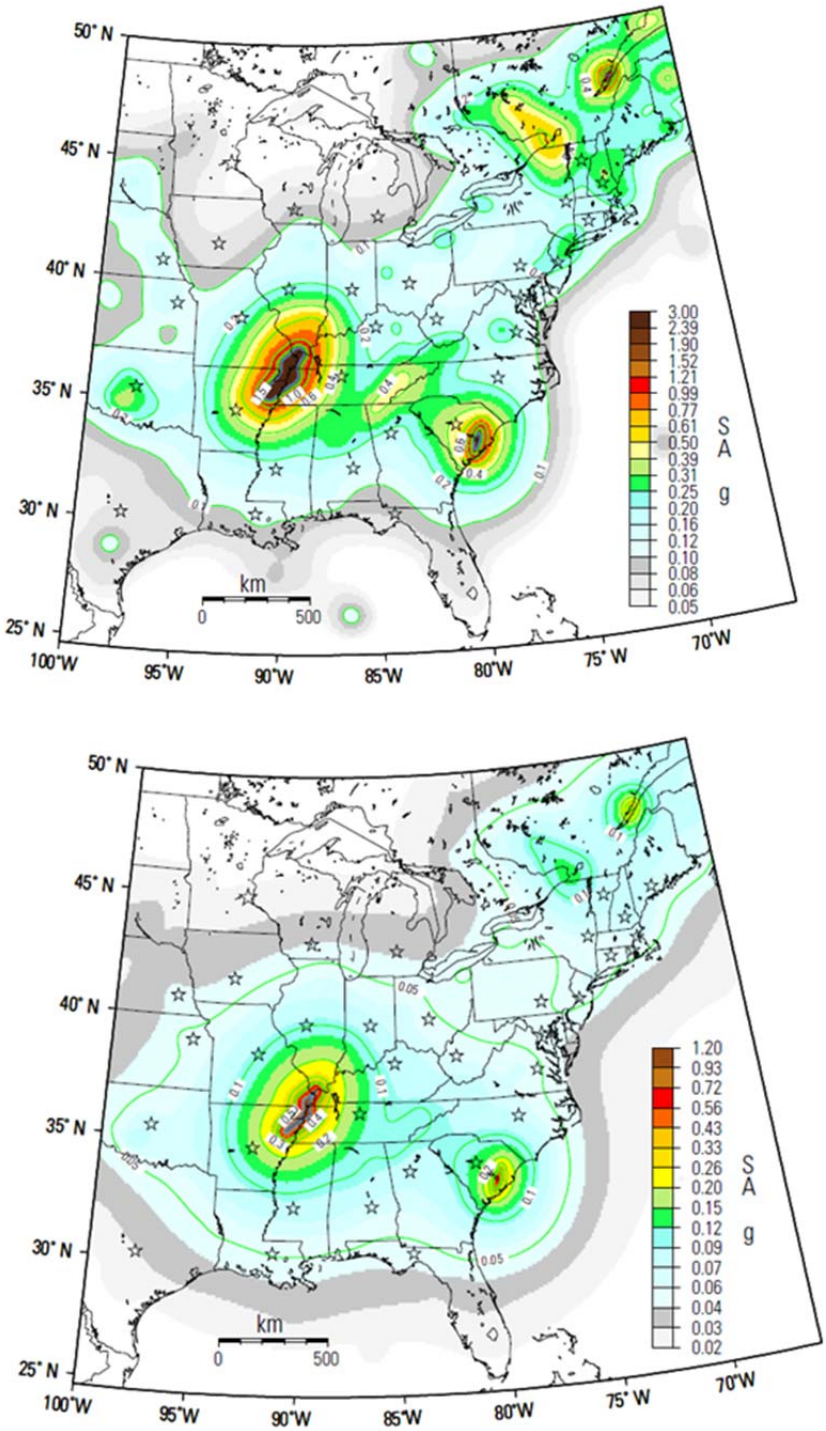

Figure 1-2. NEHRP generalized seismic hazard map for the Central and Eastern United States (from earthquake.usgs.gov/hazards/). Top shows the 0.2-second spectral acceleration (SA) ordinate and Bottom shows the 1.0-second ordinate for 2500 year motions.

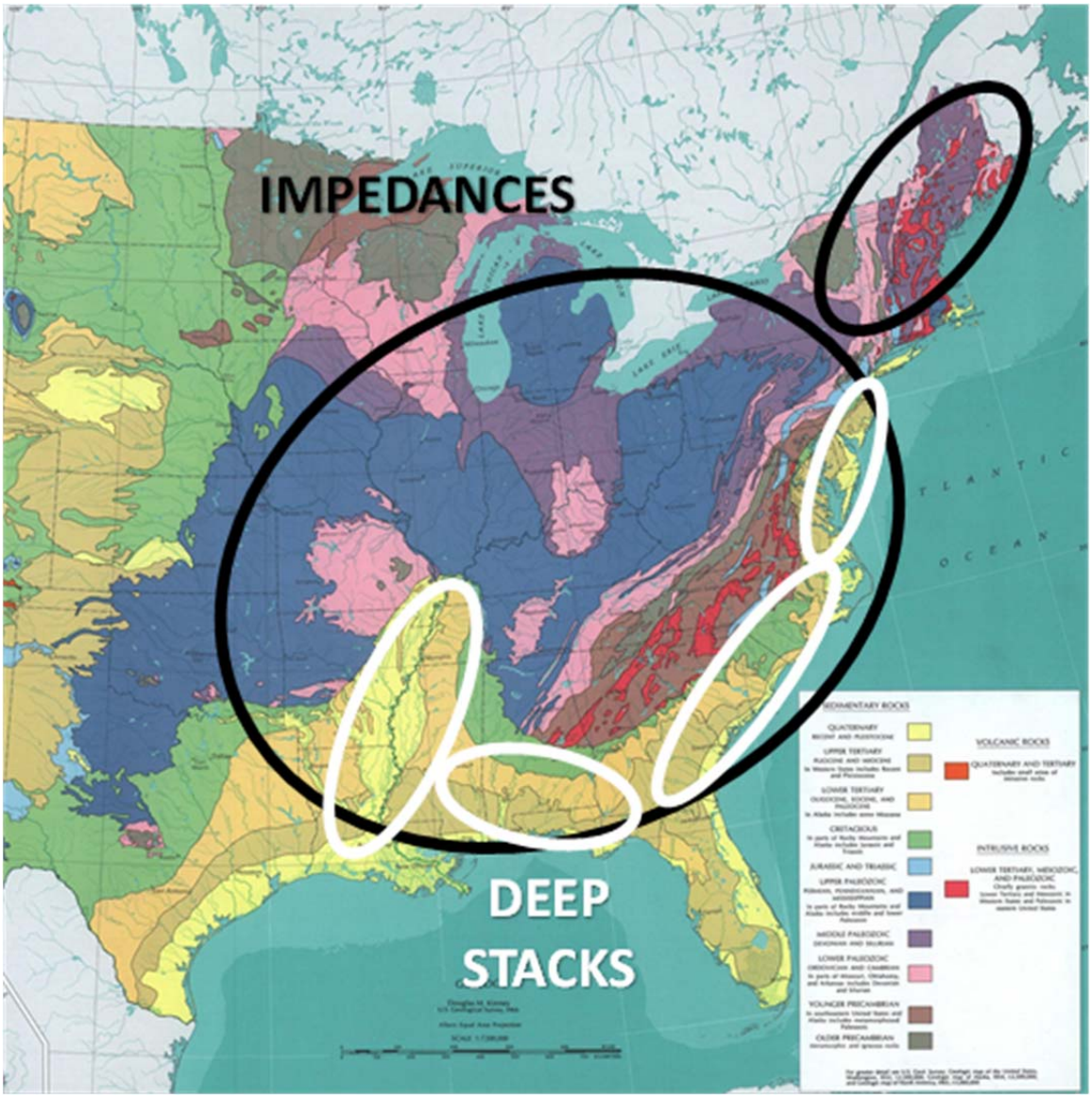

Figure 1-3. Geologic map of CEUS indicating locations of impedances (black ovals) and deep stacks (white ovals).

Figure 1-4 provides a geologic map of South Carolina showing the approximate location of the Fall Line generally running from the southwest to the northeast of the state. This geologic boundary is the intersection of the Coastal Plain and Piedmont geologic provinces. The Piedmont lies northwest of the Fall Line and the Coastal Plain is to the southeast. Columbia is located along the Fall Line in the middle of the state situated approximately 160 km to the northwest of Charleston. Figure 1-5 shows an illustrative cross section drawn from Columbia at the northwest to Charleston at the southeast; the line roughly corresponds to the black dashed line shown in Figure 1-4. Hard rock is relatively shallow near Columbia at the left with the coastal plain sediment wedge increasing in thickness to over 800 m beneath Charleston at the right. The generalized cross section shows that the geologic profile is not the same throughout South Carolina and indicates that site response behavior should not be the same across the state.

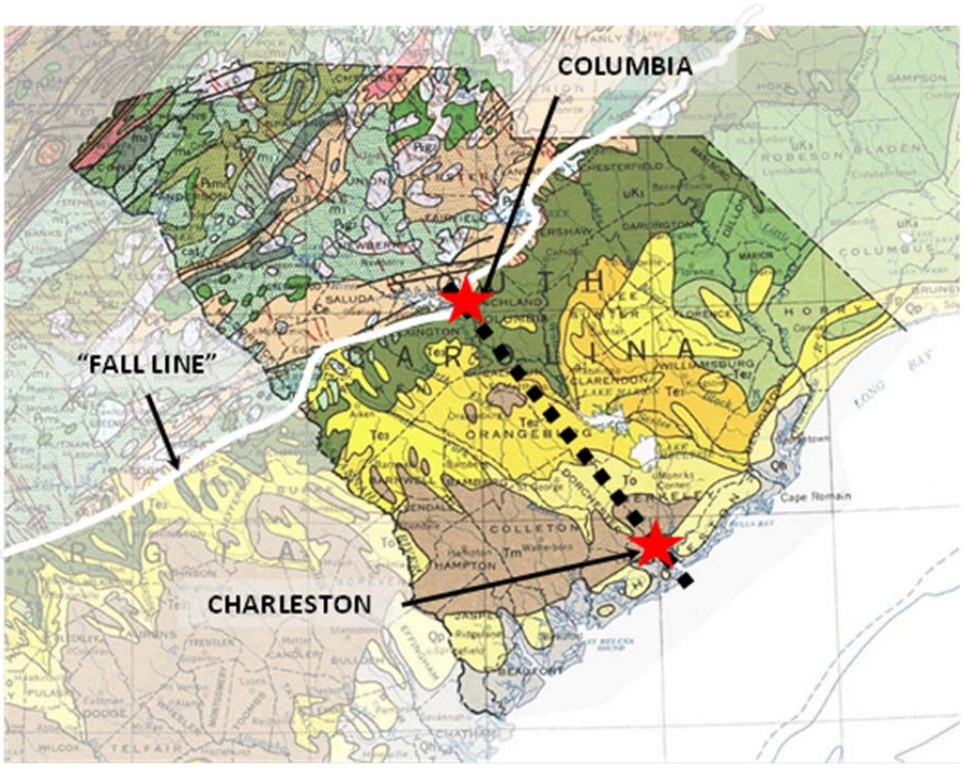

Figure 1-4. Geologic map of South Carolina showing Columbia, Charleston and the Fall Line.

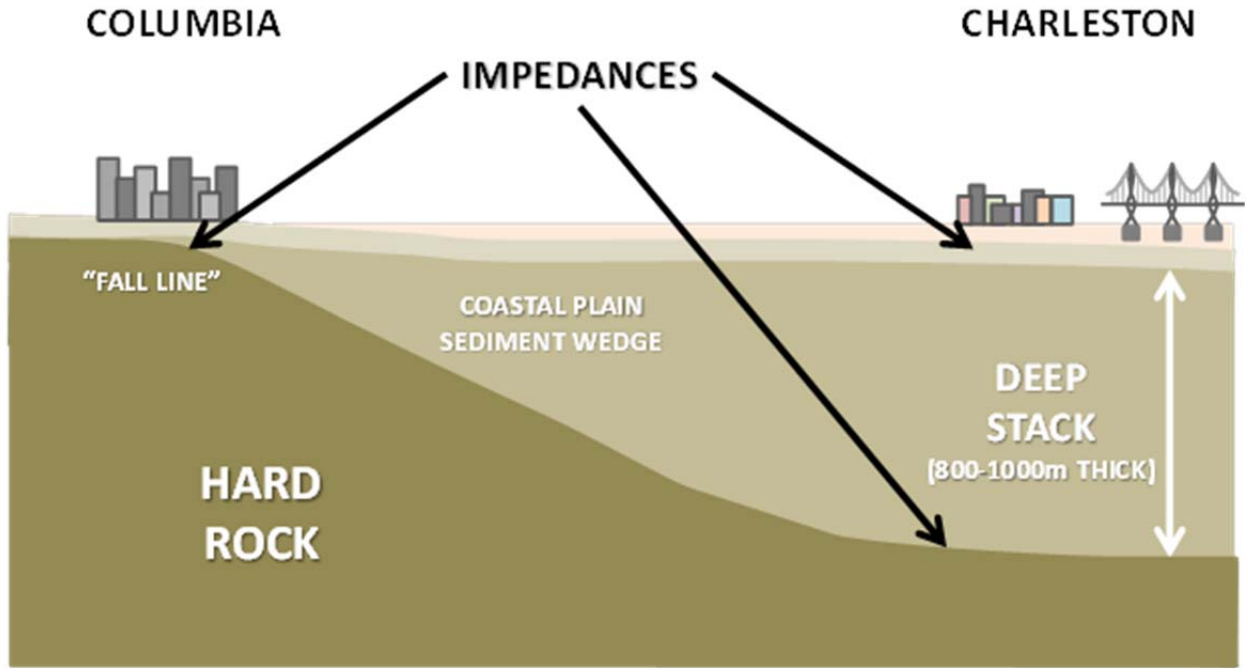

Figure 1-5. Cross-section illustrating geologic profile from Columbia to Charleston. Impedances are located throughout the state and the coastal plain sediment wedge increases to nearly 1000 meters in thickness beneath Charleston.

Site response studies of Columbia and Charleston, South Carolina, subsequently presented, indicate that seismic practitioners need to perform site specific site response studies for sites in the central and eastern United States. Performing site specific response analyses is very challenging for CEUS practitioners due to lack of experience, lack of comprehensive strong ground motion datasets, large uncertainty, and a lack of guidance. These unique challenges ultimately lead to an inconsistency of product amongst CEUS seismic engineering practitioners. Region-specific site classifications and site amplification factors accounting for impedances and deep stacks are needed to provide consistency and address these unique challenges.

2. COLUMBIA, SOUTH CAROLINA

Columbia, South Carolina is located along the Fall Line as previously shown in Figure 1-4. Soil stacks in the area are generally on the order of 15 to 40 m in thickness with shear wave velocities ranging from 100 to 500 m/sec sitting above a highly variable weathered rock typically ranging from zero to 250 m in thickness atop hard rock. Sharp contrasts in stiffness close to the ground surface are created between the rock and near surface soils. Figure 2-1 shows a typical Columbia soil site sitting atop a range of weathered rock profiles compared to the NEHRP generalized velocity profile.

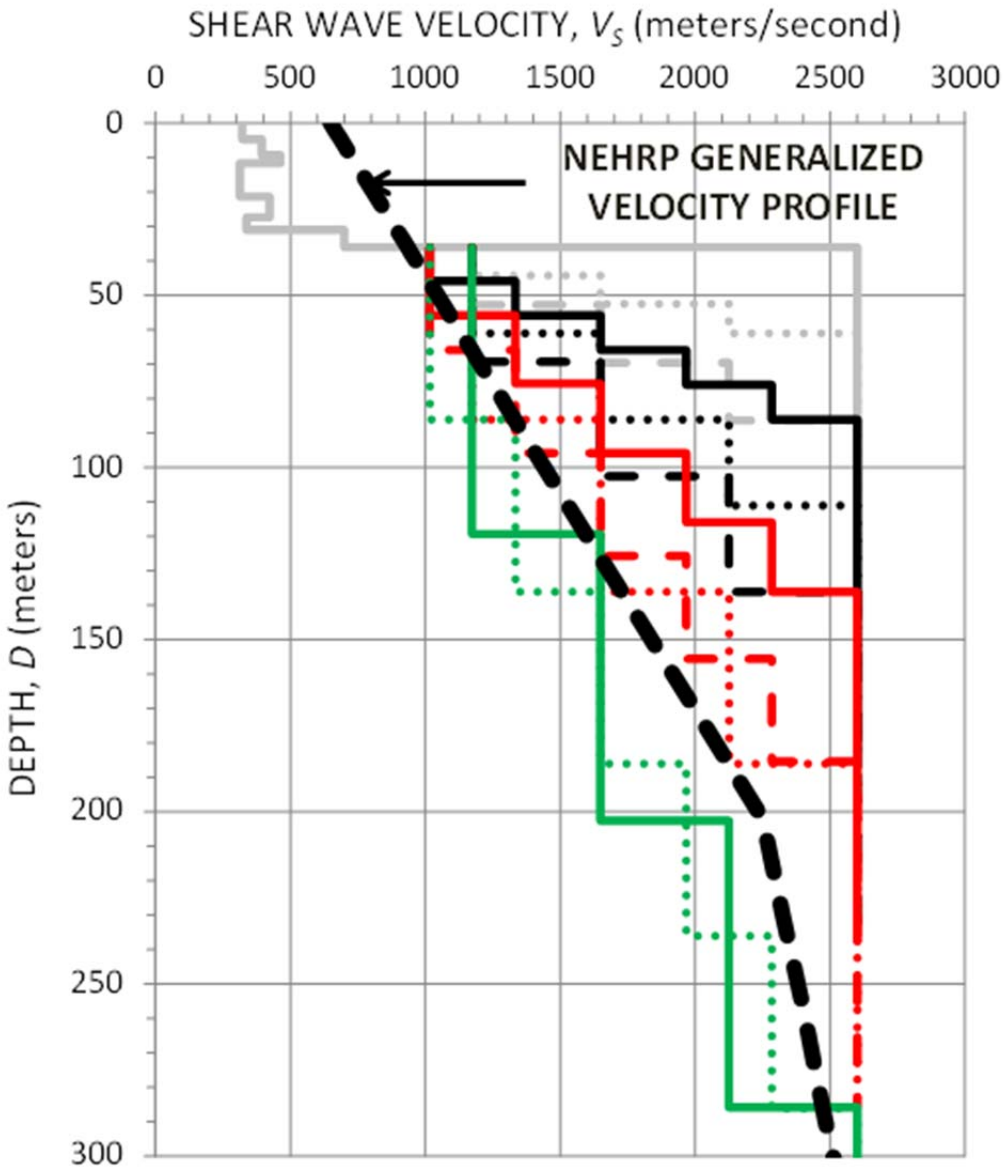

Figure 2-1. Shear wave velocity profiles used for parametric site response studies of weathered rock profile in Columbia compared to the NEHRP generic curve.

The smooth NEHRP velocity profile does not model the weathering of the rock surface and the resulting impedances with near-surface soils. Subsequent site specific studies will show how ground surface response in Columbia is sensitive to the following parameters:

1. Impedance ratio or ratio of stiffness change between geologic layers

2. Transition of the impedance or rock surface weathering

3. Period content and level of motions entering the impedance

4. Specific site conditions sitting atop the impedance

Site specific site response analyses accounting for the above listed parameters show that impedances can commonly lead to site response predictions not captured by NEHRP amplification factors in the CEUS.

Site specific studies of Columbia are performed using the equivalent linear program SHAKE (Schnabel et al. 1972). The dynamic soil properties for the profiles are modeled with shear modulus reduction and hysteretic damping curves from Vucetic and Dobry (1991) for clays using a plasticity index of 15 and an average depth of 10 m, and Ishibashi and Zhang (1993) for sands using average depths of 1.5, 4.5, 9.1, 21.3 and 27.4 m. Figure 2-2 presents plots of the dynamic soil properties as a function of shear strain including elastic curves for rock. The studies use synthetically generated hard rock motions to model a moment magnitude 7.3 earthquake at an epicentral distance of 123km, corresponding to the 1886 event. The ground motions were synthetically generated using the latest techniques and understanding of CEUS earthquake motion attenuation developed by Dr. Martin Chapman at the Virginia Tech Seismological Observatory (personal communication).

The impedance ratio or impedance contrast between geologic layers has a significant influence on predicted ground surface response. The impedance ratio is defined as the shear wave velocity of underlying material normalized by the shear wave velocity of overlying material. Motions entering the impedance are sensitive to the change in stiffness and can be significantly amplified or de-amplified depending on the impedance ratio. Figure 2-3 (top) shows a Columbia soil site with an average shear wave velocity of 400 m/sec sitting atop four different values of rock velocity; 700, 1650, 2600 and 3550 m/sec. These values correspond to impedance ratios of 1.8, 4.1, 6.5, and 8.9, respectively. Site response analysis was performed for each impedance ratio using one hard rock motion. Figure 2-3 (bottom) presents the resulting surface response spectra showing that as the impedance ratio increases the amplification of rock motions generally increases. These results indicate that modeling the range of impedance ratios within a geologic profile are important for predicting ground surface response.

Lester (2005) presented studies showing that the weathered zone of the hard rock is highly variable and uncertain along the Fall Line increasing the uncertainty in ground surface response. This unique CEUS geologic condition creates a challenge for predicting ground surface response. Shear wave velocities of the weathered hard rock can vary from 2600 m/sec to 1000m/sec over a 25 to 250 m range in thickness. Hard rock can often be found close to the

ground surface with minimal if any weathering. Figure 2-4 (top) shows 11 different weathered rock profiles with a range of thicknesses (25, 50, 75, 100, 150, and 250 m) and number of layers (3 and 5) including one without weathering. Site response analysis was performed for the 11 different weathered rock profiles using one site profile and one hard rock motion. Figure 2-4 (bottom) presents the resulting response spectra showing a wide range in ground surface response. The results show that the weathered profile influences predicted ground surface response and contributes to the uncertainty of site response along the Fall Line where variable weathered rock is commonly found.

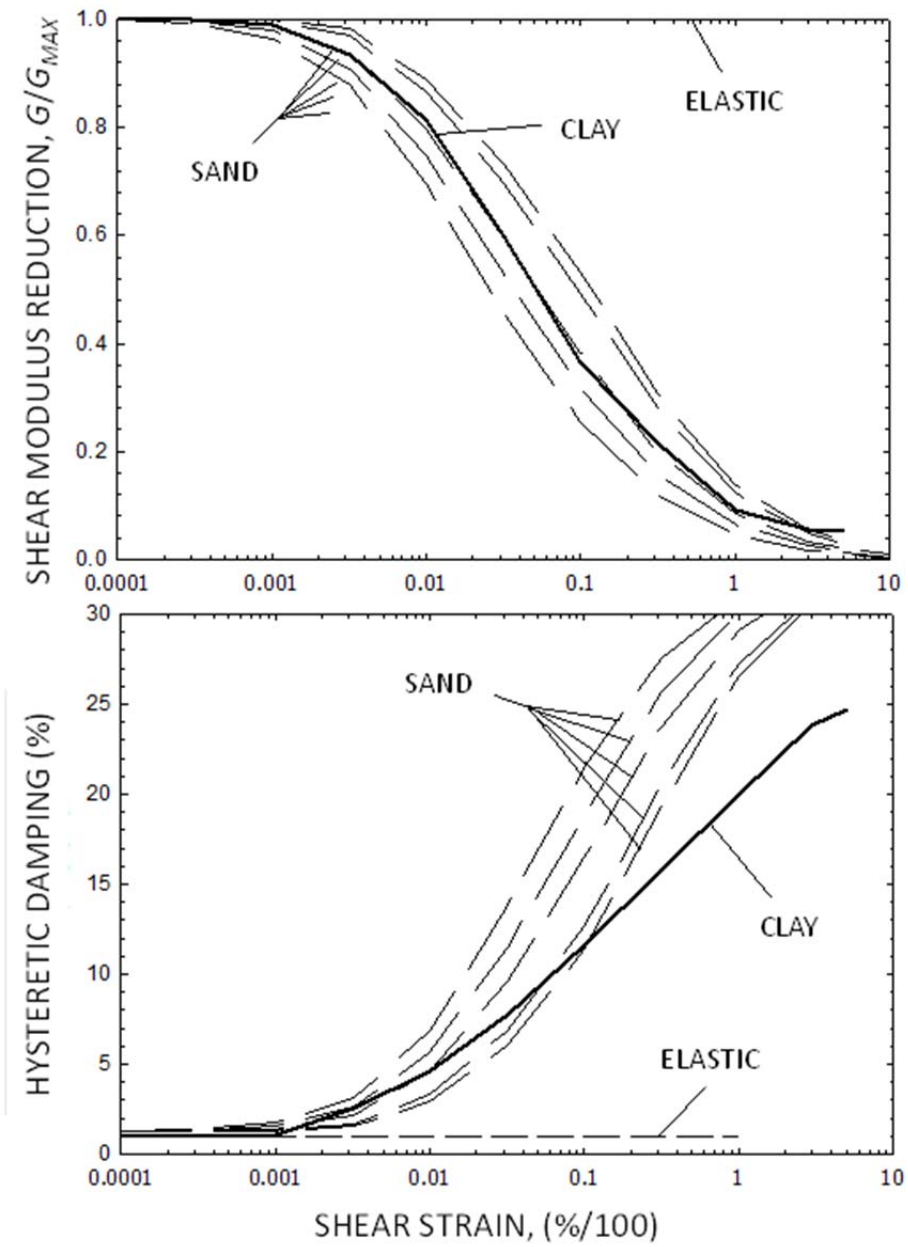

Figure 2-2. Shear modulus reduction and hysteretic damping curves used to model soil layers for Columbia.

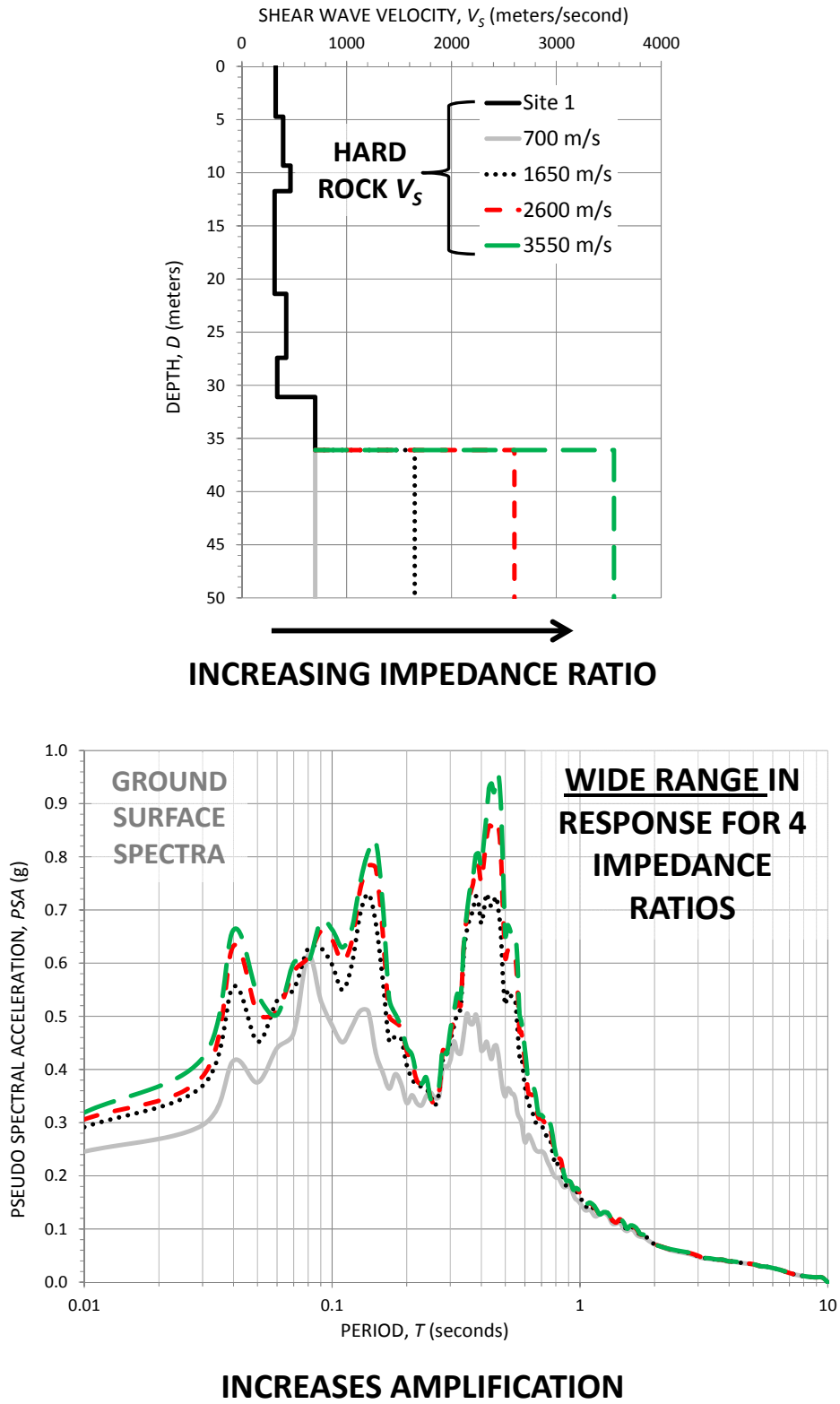

Figure 2-3. Shear wave velocity depth profile for Columbia site with four different rock shear wave velocities (impedance ratios) at the base of the model (top). Ground surface response spectra from the four impedance ratio analyses (bottom).

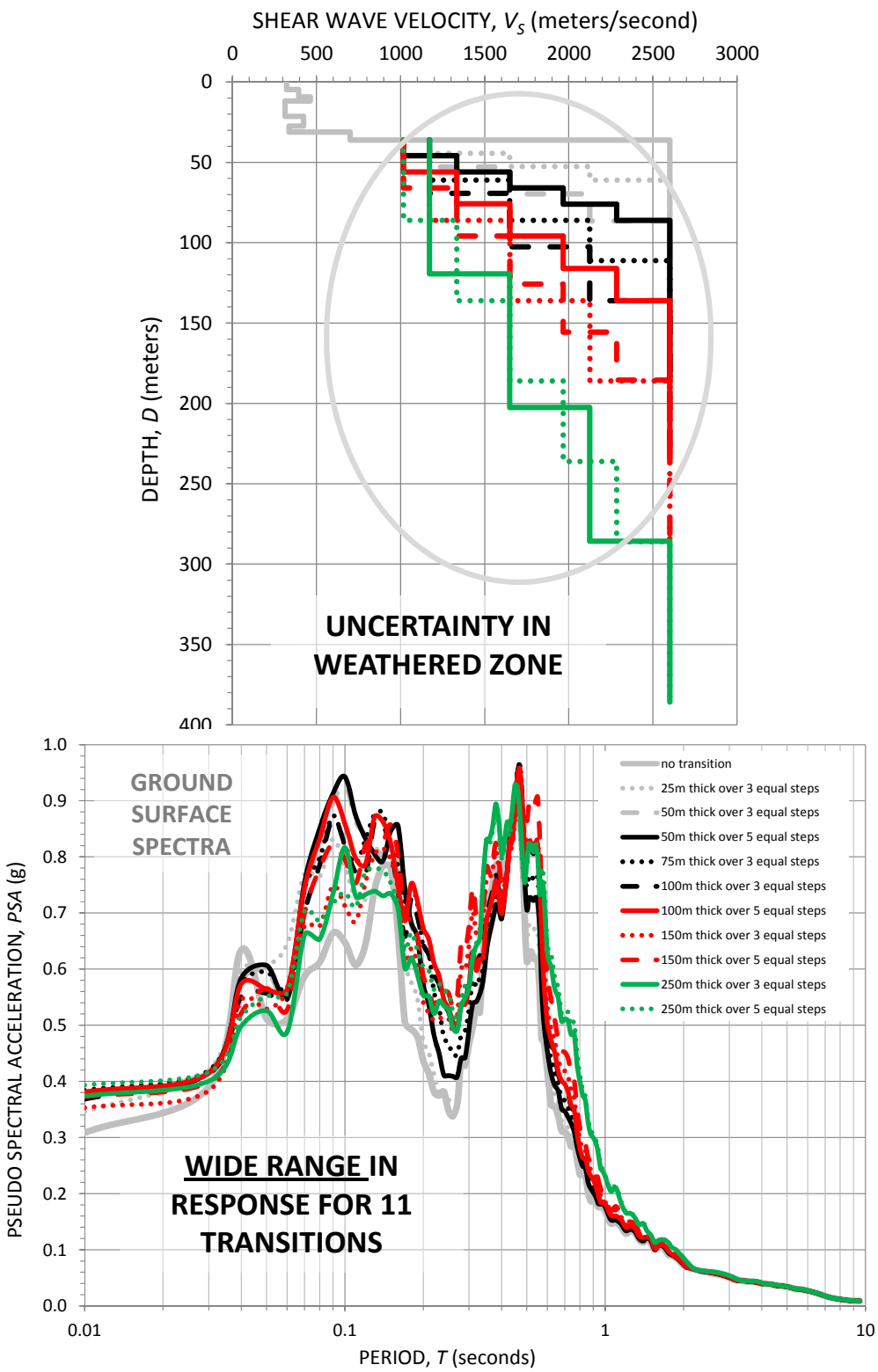

Figure 2-4. Shear wave velocity depth profiles for Columbia site with 11 different weathered rock shear wave transition models (top). Ground surface response spectra from the 11 weathered rock site response analyses (bottom).

Ground surface response in Columbia is sensitive to the period content and level of motions that enter impedances. Five motions corresponding to the 1886 Earthquake were used as the moderate input motions with average peak ground accelerations, *pga*, of 0.23g. Low and high shaking level motions were created by simply scaling the *pga* of the 1886 Earthquake to obtain *pga* values of 0.1g and 0.5g, respectively. Figure 2-5 shows the results of site response analysis performed for one Columbia site profile using 15 different rock motions corresponding to low, moderate, and high levels of shaking. The range of spectral accelerations within each level of shaking indicates that surface response is sensitive to the period content of the motion entering the impedance. Comparing the spectra across the three levels of shaking shows that amplification or de-amplifcation of the motions and the corresponding periods of resonance are also sensitive to shaking level. For example, four peaks in the low shaking level results occurring at 0.04, 0.08, 0.11, and 0.40 sec all have spectral accelerations around 0.40g. Whereas the high shaking level results show four peaks at 0.04, 0.10, 0.12, and 0.5 sec with spectral accelerations of 0.80g, 1.20g, 1.20g and 1.60g, respectively. This result highlights the importance of considering multiple earthquake scenarios when predicting surface response due to the uncertainty of earthquake sources and lack of a strong ground motion database in the CEUS.

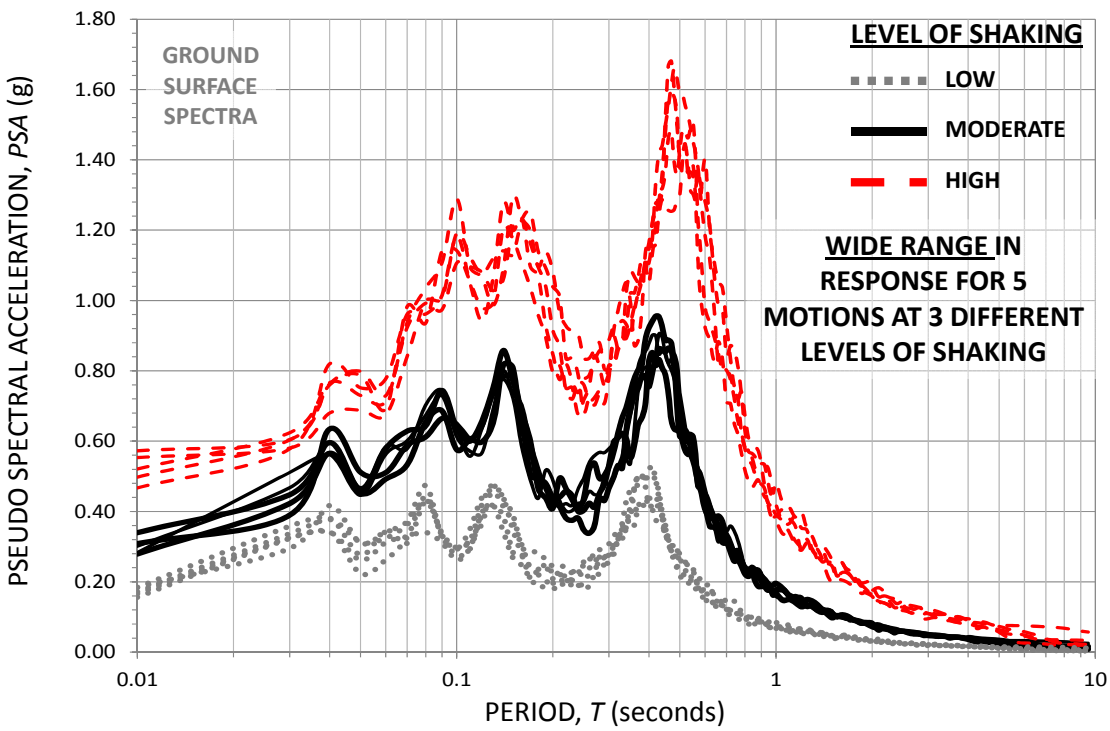

Figure 2-5. Ground surface response spectra from five motions as three different levels of shaking (low, moderate, and high) for one Columbia site profile.

The site specific soil conditions including depth to rock and stiffness contrasts at locations around Columbia and along the Fall Line can vary significantly. Figure 2-6 (top) provides plots of shear wave velocity as a function of depth for seven Columbia soil sites. Site response analysis was performed for the seven Columbia sites using the same hard rock motion without a weathered transition. Figure 2-6 (bottom) presents the resulting ground surface spectra showing that the surface response is sensitive to the depth and layering of the near surface sediments

sitting atop rock. Site 7 shows two dominant peaks of resonance occurring at 0.21 and 0.59 sec with spectral accelerations around 0.7g while Site 5 shows two main peaks at 0.10 and 0.21 sec with spectral accelerations of 1.0g and 1.4g, respectively. These widely varying results would potentially lead to two very different seismic design requirements given a specific structure. These results show that defining the thickness and stiffness of soils atop an impedance is very important for surface response prediction. Haase et al. (2011) show similar findings for Evansville, Indiana near the New Madrid and Wabash Valley Seismic Zones where the ground surface response is shown to be correlated with depth to bedrock.

The preceding site response studies illustrate the potentially wide range in surface response and the importance of identifying four parameters when performing site response analysis in Columbia, South Carolina and other similar geologic settings in the CEUS: impedance ratio or contrast in stiffness between geologic layers, transition of the impedance or rock surface weathering, period content and level of motions entering the impedance, and specific site conditions sitting atop the impedance. Site specific studies of Columbia sites indicate that unique CEUS geologic conditions may not be fully captured by the generalized NEHRP procedures.

The NEHRP site amplification factors were derived from ratios of response spectra; more specifically the average ratio of ground surface response spectra normalized by "B-C Boundary" response over different period ranges and for different site classifications defined by ranges of V_{S30}. For comparison with the NERHP values, ratios of response spectra from the site specific results were computed by dividing the ground surface response spectra by 125% of the hard rock spectra or the "B-C Boundary" response. Site response analyses of the seven Columbia sites from Figure 2-6 (top) and the 11 weathered rock transitions from Figure 2-4 (top) were performed. Five synthetic rock motions modeling the 1886 Charleston Earthquake representative of 2500-year motions were used as input with a M_w 7.3 at an E_D of 123km with an average *pga* of 0.23g. Figure 2-7 presents the computed ratio of response spectra as a function of period for three class C sites (top) and four class D sites (bottom) including mean (μ) and plus and minus one standard deviation (σ) curves. The NEHRP factors for the short period site amplification factor, F_a, and mid to long period range site amplification, F_v, are plotted over the 0.1 to 0.5 second 0.4 to 2.0 sec ranges, respectively. NEHRP F_a values for both class C and D sites are generally 25% to 60% lower than the mean ratios of response spectra computed from the site specific studies. The computed F_v values for both class C and D Columbia sites are typically higher than the NEHRP values from 0.4 to 0.8 sec and lower than NEHRP values from 0.8 to 2.0 sec.

Figure 2-8 presents the NEHRP (dashed line) and computed (solid dots with plus and minus one standard deviation lines) site amplification factors plotted as a function of V_{s30}. The F_a values (top) show that the mean predicted amplification factors are generally 50% to 80% higher than the NEHRP in the 0.1 to 0.5 sec range. The F_v values (bottom) from the site specific studies of Columbia sites were computed using the NEHRP 0.4 to 2.0 sec period range. The mean site specific factors computed in this range are generally equal to or less than the NEHRP factors for the range of V_{S30} in Columbia. The results presented in Figures 2-7 and 2-8 indicate that the NEHRP site amplification factors do not capture the effect of impedances close to the ground surface and uncertainty in rock weathering suggesting the need for region specific site amplification factors and hazard maps.

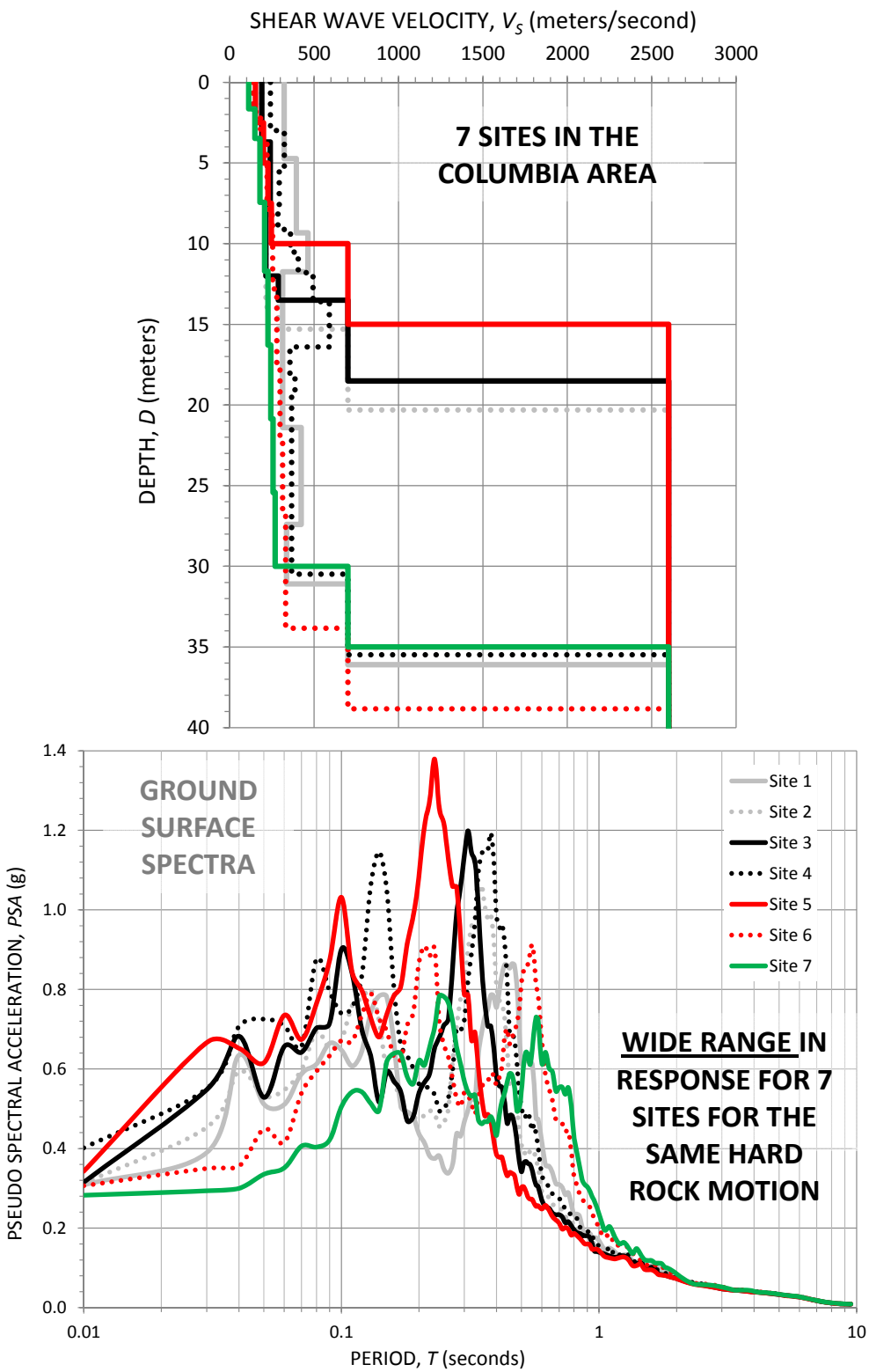

Figure 2-6. Shear wave velocity depth profiles for seven Columbia sites (top). Ground surface response spectra from site response analyses of the seven Columbia sites using the impedance with hard rock and the same hard rock motion (bottom).

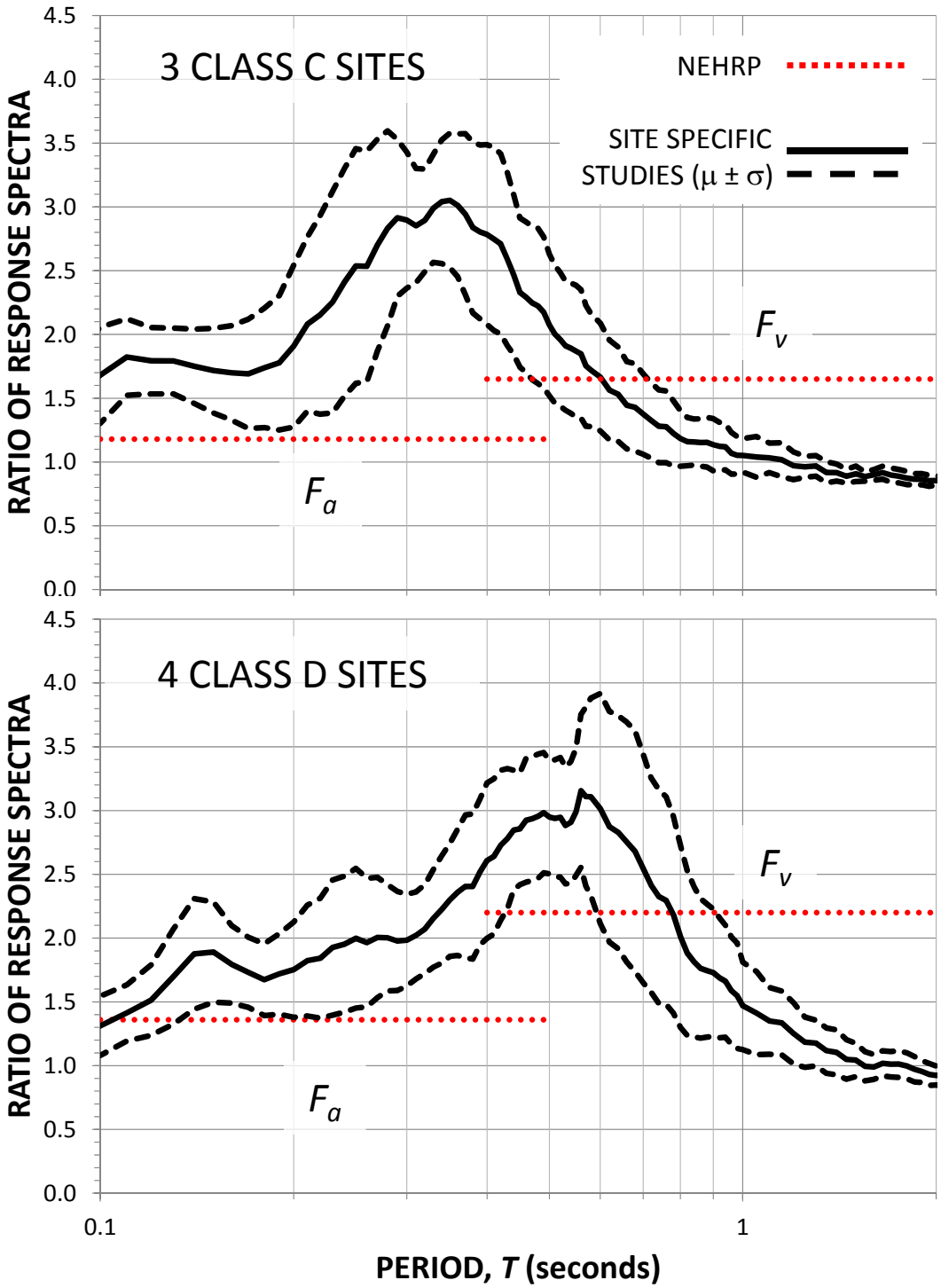

Figure 2-7. Ratio of response spectra computed from site specific studies compared to NEHRP site amplification factors. Three class C sites (top) and four class D sites (bottom) from Columbia.

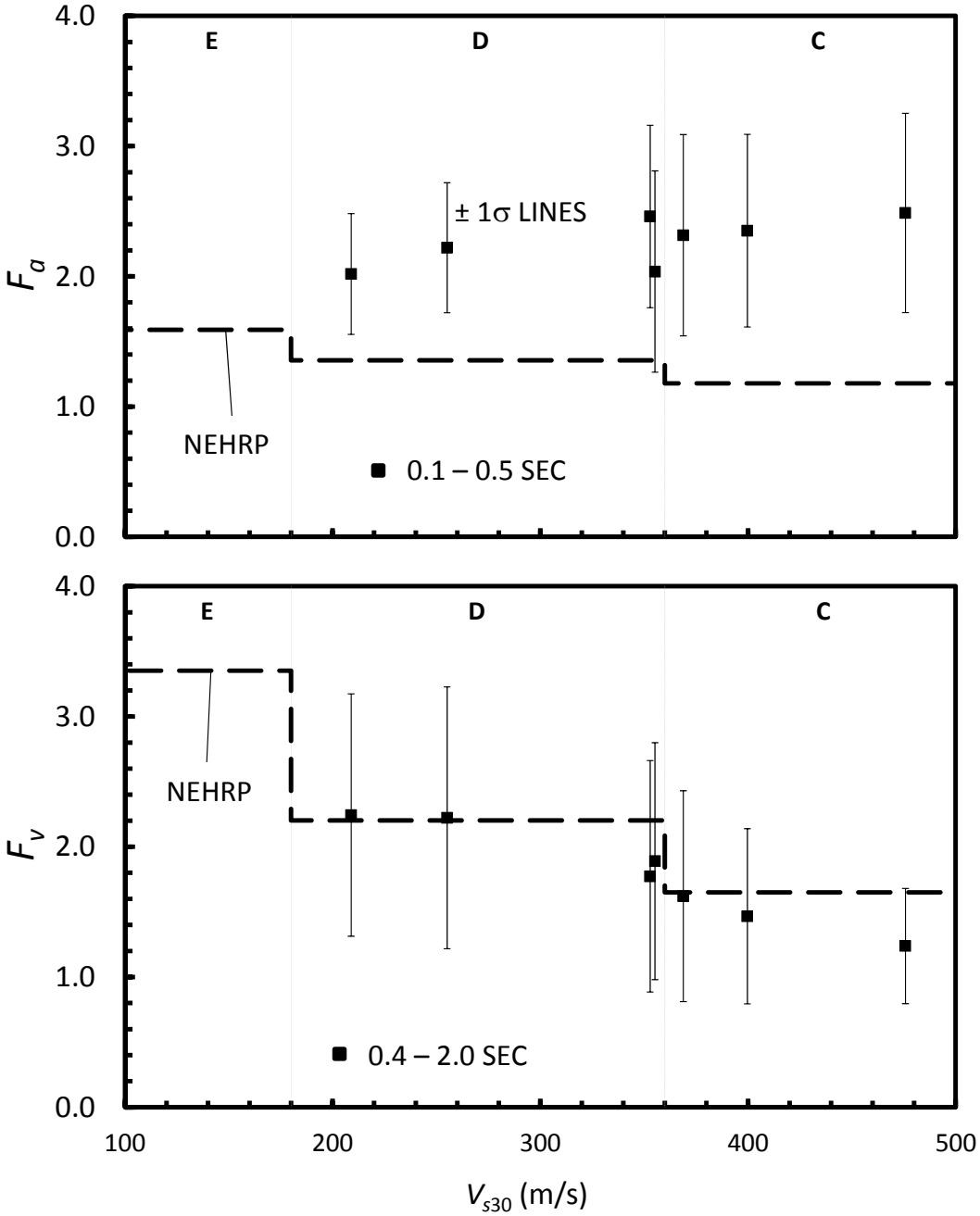

Figure 2-8. Site amplification factors computed from site specific studies of Columbia compared to NEHRP values. The short-period amplification factor, F_a, (top) and the mid-period amplification factor, F_v, (bottom) are shown as a function of V_{s30}.

Spectral Acceleration response spectra show similar trends. Mean, minimum, maximum and plus and minus one standard deviation curves computed from the results of the Columbia site specific studies are plotted on Figure 2-9; NEHRP curves (2500-year) for site class C, D, and E are plotted for comparison. The plot shows that the average site response for Columbia is better captured by the NEHRP site class E curve as compared to class D or C.

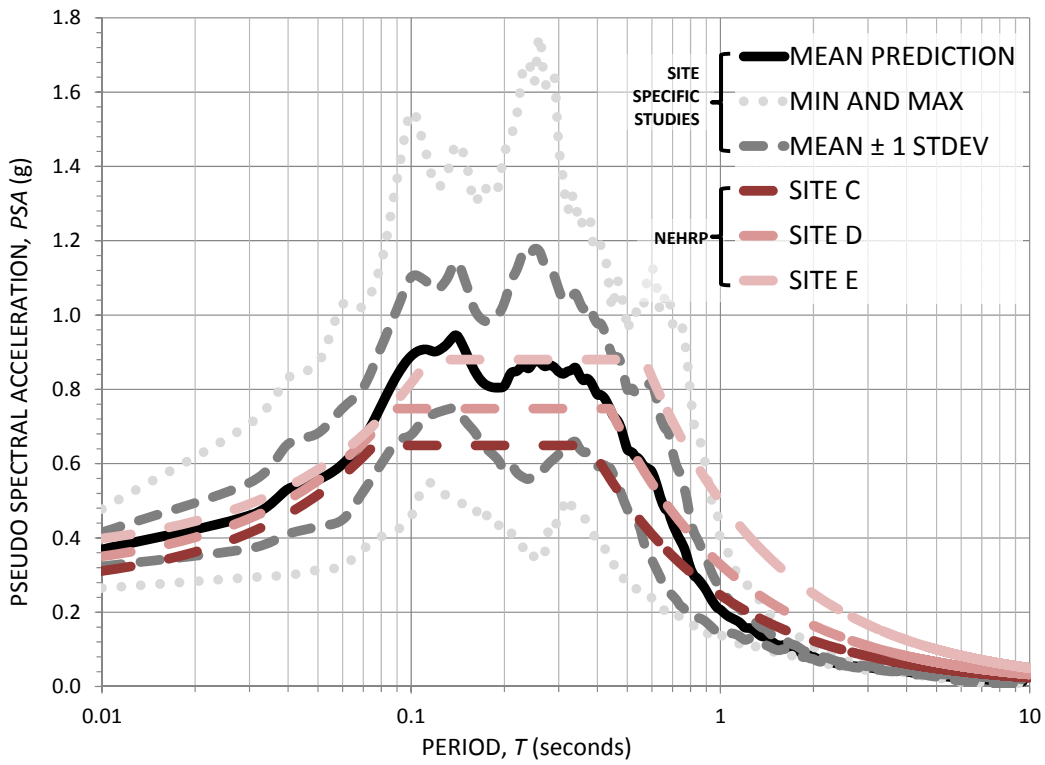

Figure 2-9. Site response spectra computed from site specific studies of Columbia sites compared to NEHRP curves.

These results further suggest the need to account for unique geologic conditions in the CEUS for developing response spectra to be used for structural design and refinement of the NEHRP procedures. The NEHRP curves indicate that amplification factors generally increase as the site classification moves towards E; this is reflected by the increase in spectral accelerations from site class C to D and finally E in Figure 2-9.

Results from site specific analysis of one site Class C and one site Class D Columbia site are plotted along with respective NEHRP spectra in Figure 2-10. The site specific curves are plotted as solid lines with the NEHRP curves plotted with dashed lines; site Class C is plotted as red and site Class D as black. The site specific curves show that the site Class C site amplifies the same hard rock motion more than the site Class D site. This result contradicts the behavior modeled with the NEHRP procedures. The short period amplification factors presented in Figure 2-8 show similar results where the computed factors from site specific studies are generally higher for Class C versus Class D sites. These findings suggest that the NEHRP site classifications and the V_{s30} parameter do not capture unique site response characteristics of CEUS geology as illustrated with geologic conditions found in Columbia, South Carolina.

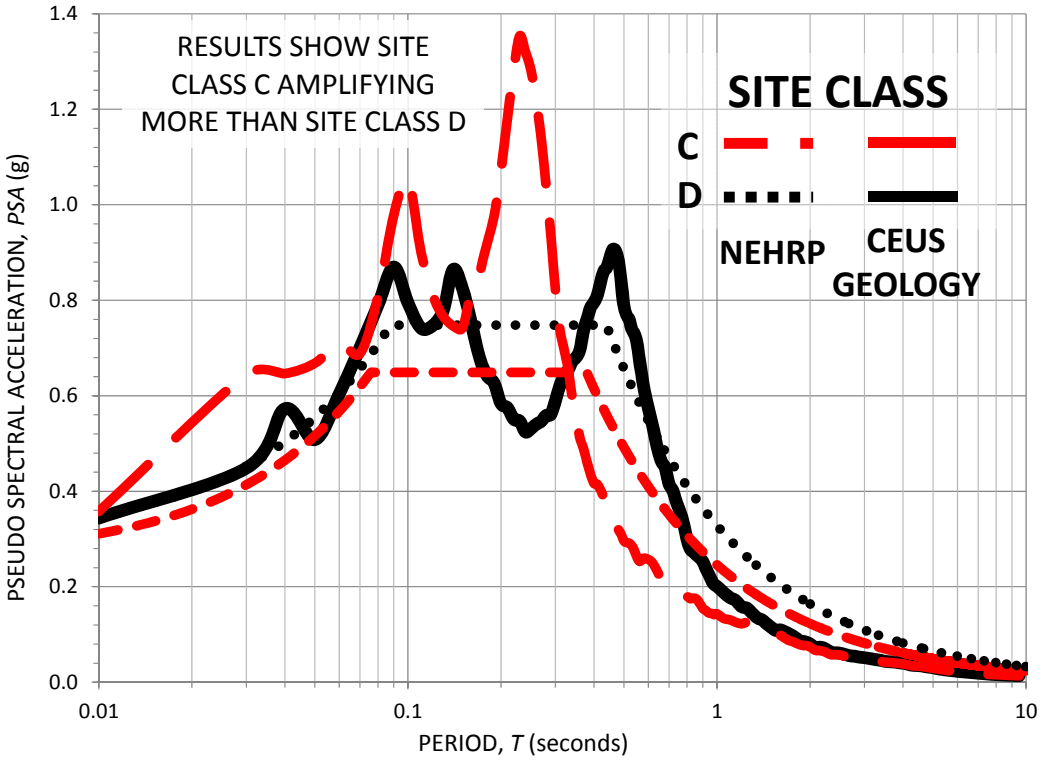

Figure 2-10. Site specific studies of class C and class D Columbia sites compared to NEHRP curves indicating class C amplifying more than class D.

3. CHARLESTON, SOUTH CAROLINA

Charleston, South Carolina is located approximately 160 km southeast of Columbia as previously shown in Figure 1-4 in the Coastal Plain geologic province. Near surface soils generally consist of quaternary sediments ranging from a few to 30 m in thickness sitting atop tertiary clays locally referred to as “Cooper Marl”. The contrast in shear wave velocity for near surface soils sitting atop the marl in Charleston is very similar to the impedances with rock previously shown for Columbia. Figure 3-1 provides shear wave velocity profiles as a function of depth for the seven Columbia sites and eight Charleston sites. In general, Charleston sites display comparable site response behavior to Columbia sites given that both locations contain near surface soils which have a stiffness contrast with the underlying stratum; weathered hard rock in Columbia versus marl in Charleston. The effect of impedances on ground surface response plays a significant role in the uncertainty of ground surface response in Charleston. Site response studies presented by Chapman et al. (2006) of shallow geotechnical subsurface data from 281 Charleston sites show that the depth to the tertiary sediments and the stiffness contrast between quaternary and tertiary sediment controls predicted ground surface response around Charleston and in the Coastal Plain.

The main difference between Columbia and Charleston is the deep sedimentary wedge sitting beneath the near surface soils in Charleston. Figure 3-2 compares the NEHRP generalized velocity profile to a typical Charleston soil site with approximately 80 m of quaternary and tertiary material sitting atop the sediment wedge with an uncertain depth, generally ranging from 700 to 1,000 m along the Atlantic Coast of South Carolina. The smooth NEHRP shear wave velocity profile does not model the deep sediment stack, the impedance contrast between hard rock and the sediment stack, or the impedance contrast between the sediment stack, tertiary, and quaternary sediments. Subsequent site specific studies will show how ground surface response in Charleston is sensitive to the following parameters:

1. Properties of the deep sediment stack

2. Properties of sediments sitting atop the deep sediment stack

3. Period content and level of motions entering the deep stack

Site specific site response analyses accounting for these parameters show that the effects of the deep stack and near surface impedances can commonly lead to site response predictions not captured by the NEHRP procedures. The results of these studies suggest that region specific factors are needed to capture these unique CEUS geologic conditions.

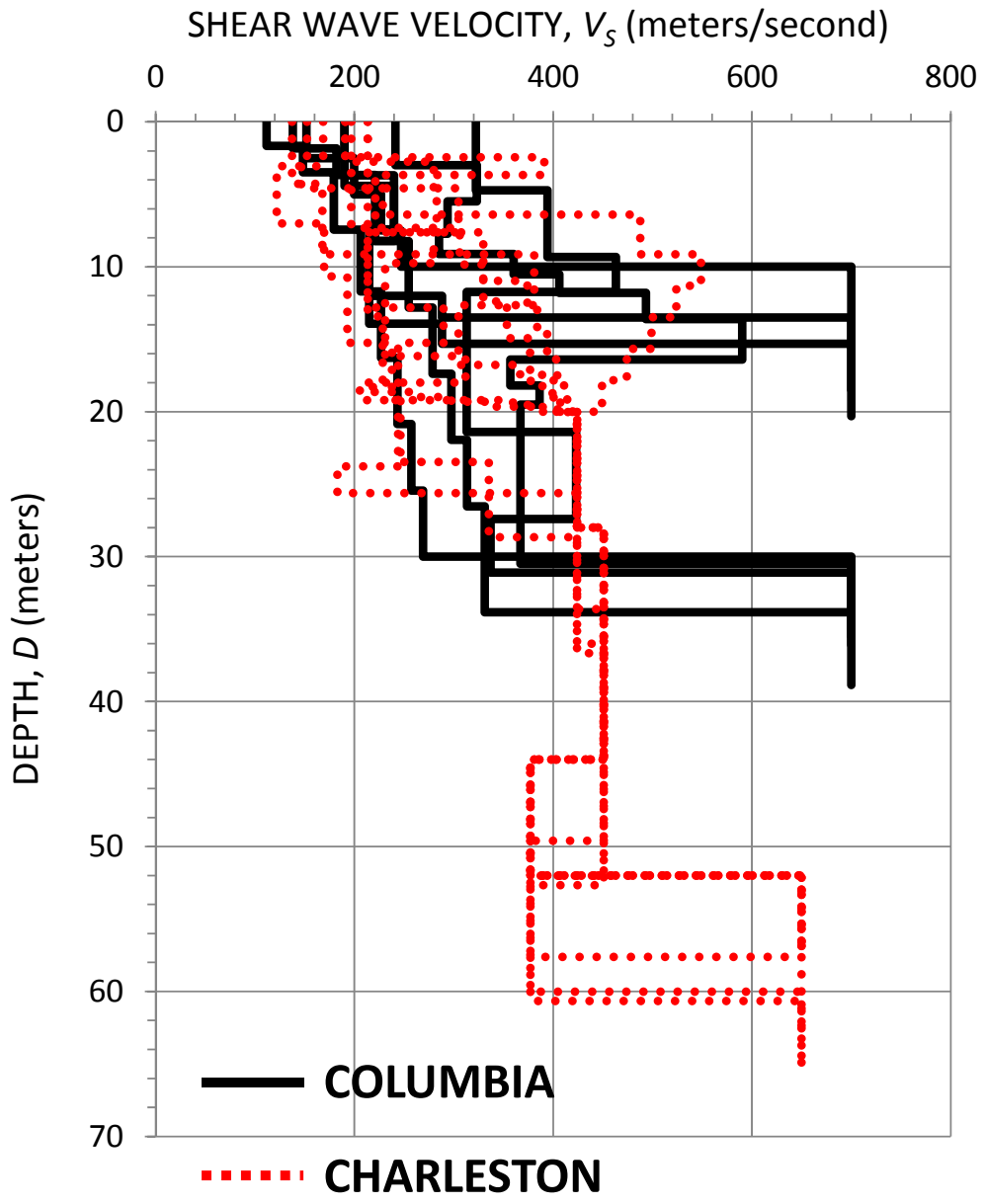

Figure 3-1. Shear wave velocity depth profile comparing seven sites in Columbia to eight sites in Charleston.

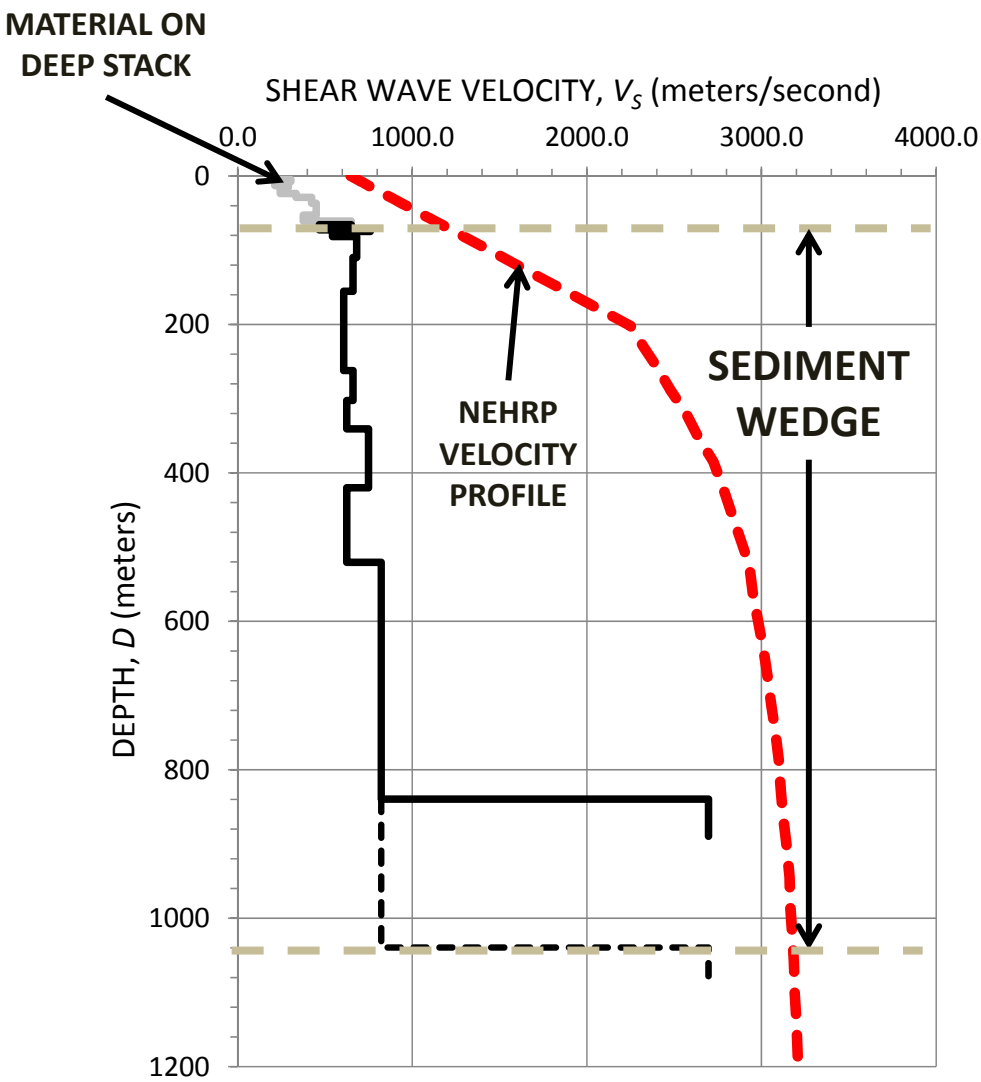

Figure 3-2. Shear wave velocity profile as a function of depth for Charleston showing near surface sediments sitting atop the Coastal Plain sediment wedge compared to the generic NEHRP profile.

Site specific studies of Charleston are performed using the equivalent linear program SHAKE (Schnabel et al. 1972) and the nonlinear program DEEPSOIL Version 2.6 (Hashash, 2005). The dynamic soil properties for the Charleston profiles are modeled with shear modulus reduction and hysteretic damping curves from Vucetic and Dobry (1991) for clays using a plasticity index of 15 and an average depth of 10 meters, Ishibashi and Zhang (1993) for sands using average depths of 1.5, 4.5, 7.5, 10.5, 13.5 and 18.3 m, and Assimaki et al. (2000, 2001) for the deep stack using confining pressures of 1153, 2165, 3041, and 4382 kPa. The dynamic soil properties for marl are based on data provided by local practitioner William Camp (personal communication). Figure 3-3 presents plots of the dynamic soil properties as a function of shear strain including elastic curves for rock. The site specific studies of Charleston use five synthetically generated hard rock motions modeling a M_W 7.3 earthquake at an E_D of 30 km corresponding to the historic 1886 event (after Chapman et al, 2006).

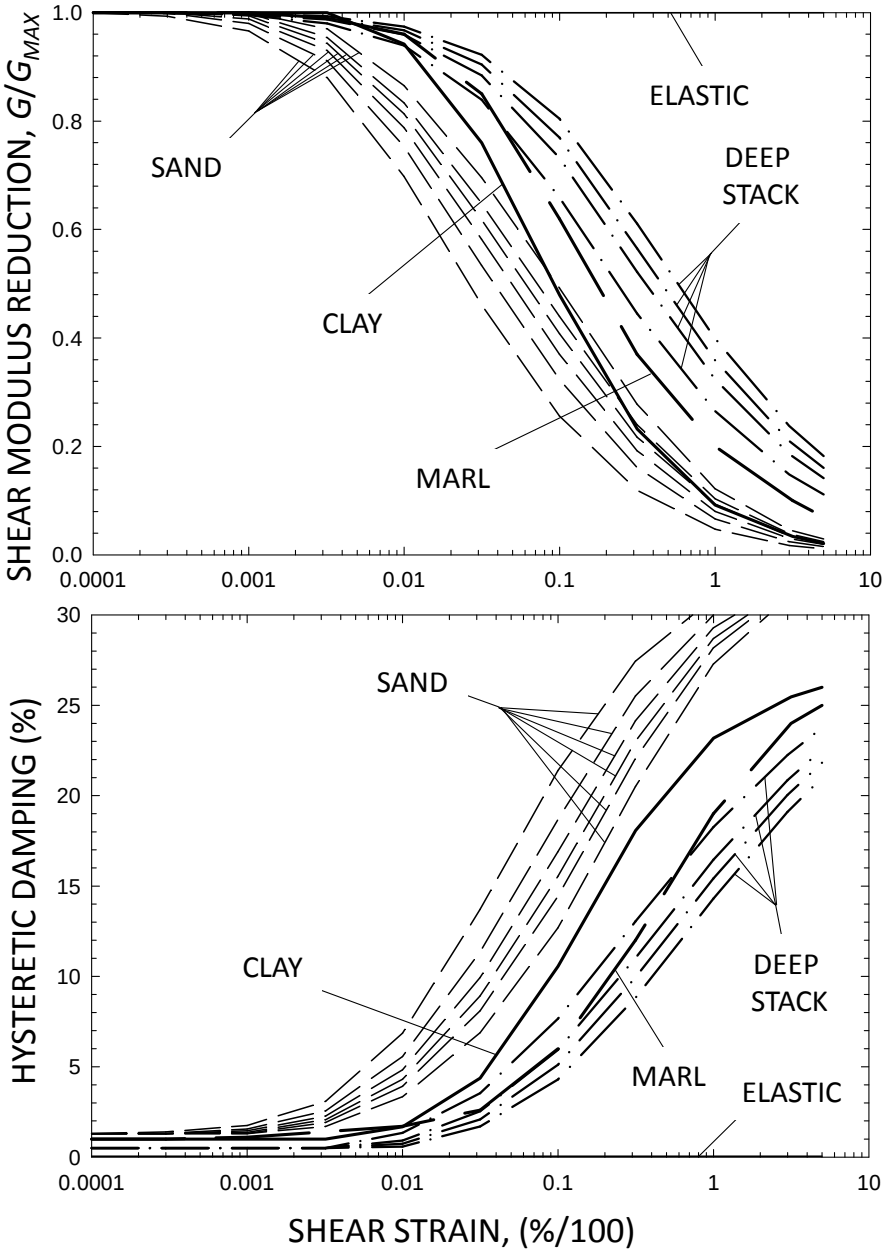

Figure 3-3. Shear modulus reduction and hysteretic damping curves used to model soil layers for Charleston.

The depth to rock and stiffness of the deep sediment stack influence the ground surface response. Figure 3-4 (top) shows five shear wave velocity profiles to investigate the effect of depth to rock with 840, 890, 940, 990, and 1040 m and deep stack stiffness with an 840 m stack with a 30% increase in shear wave velocities. Figure 3-4 (bottom) shows that subtle changes in the spectral acceleration peaks and predominant periods of amplification occur in the mid to long period range as the depth to hard rock changes.

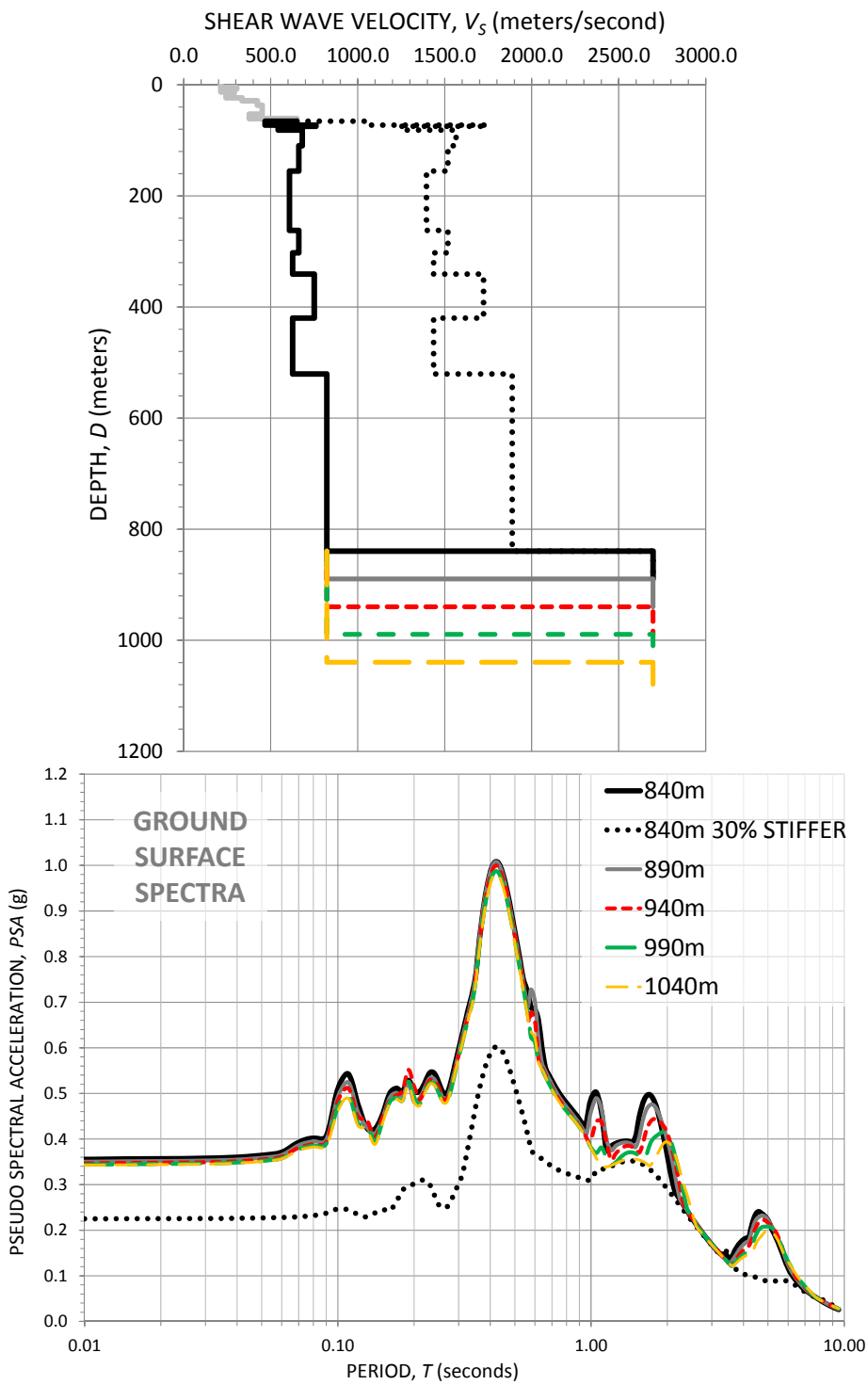

Figure 3-4. Shear wave velocity profiles (top) and ground surface response spectra (bottom) with a range in sediment wedge depth and one profile modeled with a 30% increase in stiffness.

The peaks in the ground surface response generally shift to higher periods with increased depth. The ground surface response with a 30% increase in shear wave velocity shows that the impedance occurring between hard rock and the deep sediment stack significantly changes the amplification of hard rock motions. The increase in deep stack stiffness, or reduction in impedance ratio, results in less amplification as compared to the softer sediment wedge profiles as previously shown for Columbia in Figure 2-3. Given the same near surface soil conditions, these results show that ground surface response in Charleston is sensitive to the dynamic properties of the deep sediment stack. The fundamental periods of shaking for the deep stack are a function of the thickness and stiffness and are generally estimated as $4H/V_s$, where H is the thickness of the deep stack, V_S is the average shear wave velocity of the stack, and n is the order of the fundamental period. For example, from Figure 3-4 (top), the 840 m deep profile has a V_S of 700 m/sec and an H of 780 m. Using n values of 1 and 3 provide approximations for 1st and 3rd fundamental periods of 4.5 and 1.5 sec, respectively. The ground surface response at these fundamental periods shown in Figure 3-4 (bottom) corresponds to resonance of the deep stack with the hard rock motions.

Thus far, site response analyses have been performed using the equivalent-linear method and do not directly account for soil non-linearity. Uncertainty exists with modeling the non-linear response of the deep sediment stack largely due to the lack of a strong ground motion database in the CEUS. Nonlinear solutions however, such as those developed by Youssef Hashash and Duhee Park (2001, 2002, 2004, and 2005), show that equivalent-linear solutions can over-dampen motions that are filtered through deep sediment stacks.

Site response studies were performed with equivalent-linear analysis using SHAKE and nonlinear analysis using DEEPSOIL to compare the predicted ground surface response. Figure 3-5 (top) compares the results for a Charleston site sitting on an 800 m deep sediment stack. The nonlinear solution is 50% to 100% greater than the equivalent-linear solution for shorter periods and 15% higher at the predominant period of shaking for the deep stack around 4 sec. Figure 3-5 (bottom) compares the results for the same Charleston site, however with a much shorter 250 m stack corresponding to a location between Charleston and Columbia. The ground surface response for the 250 m stack shows that amplification at shorter periods can be artificially reduced for shorter deep sediment stacks; however the effects of nonlinearity generally reduce as the deep stack thickness and impedance with rock decreases. Nonlinear modeling of deep stack effects should be considered for detailed site response studies depending on the fundamental period(s) of shaking for the deep stack and structure being analyzed.

The properties of the sediments sitting atop the deep sediment stack in Charleston are important for predicting ground surface response as evidenced in studies performed by Chapman et al. (2006) and Andrus et al. (2006). The quaternary sediments typically range in thickness from a few meters to 30 m with shear wave velocities between 150 to 250 m/sec sitting atop the tertiary marl with shear wave velocities ranging from 300 to 500 m/sec. The fundamental periods of shaking for the stacks heavily influence the ground surface response.

Figure 3-6 (top) presents shear wave velocity profiles for eight Charleston soil sites (from Chapman et al., 2006).

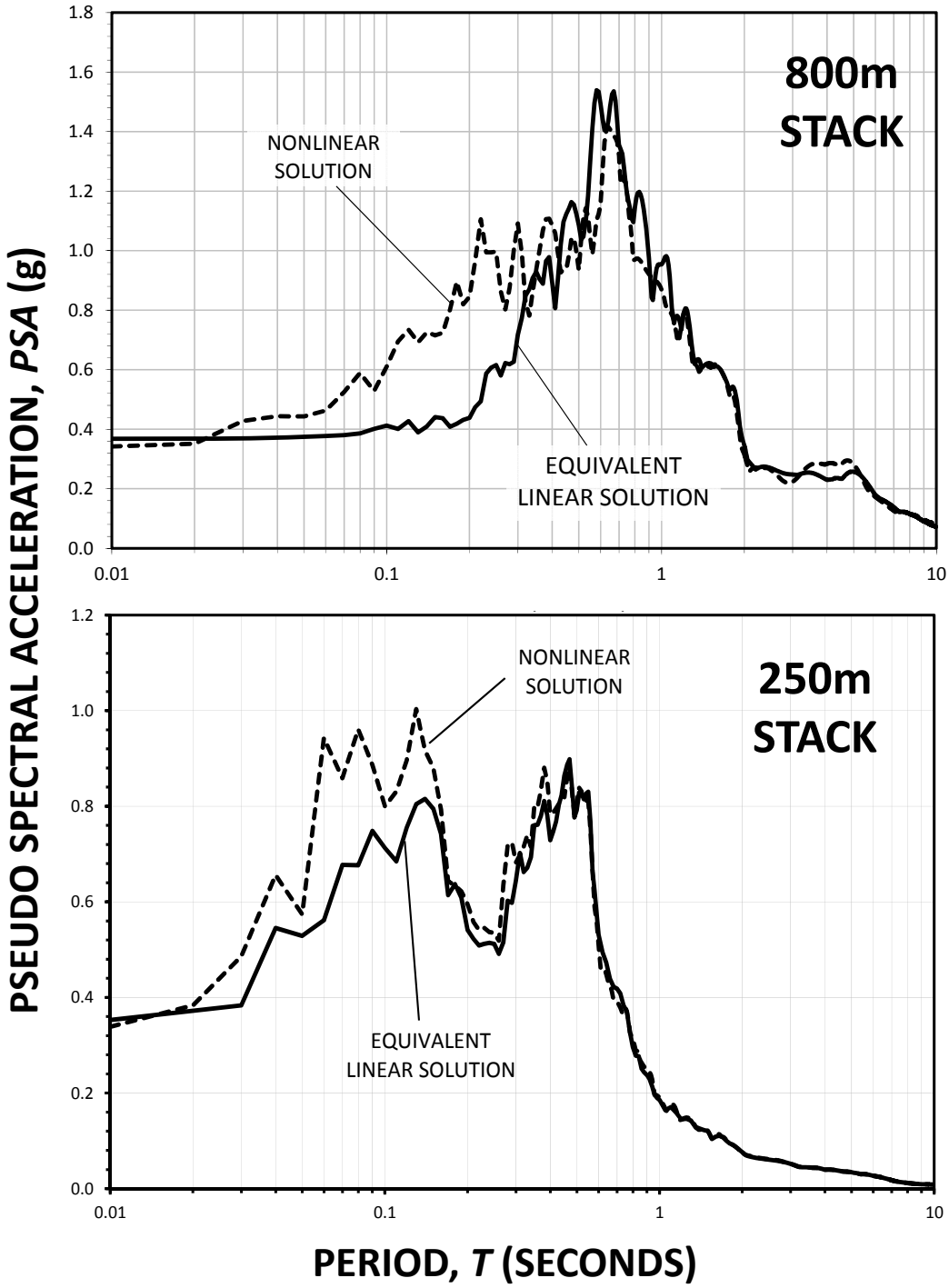

Figure 3-5. Comparison between nonlinear and equivalent linear solutions for 800m (top) and 250m (bottom) sediment wedge thicknesses.

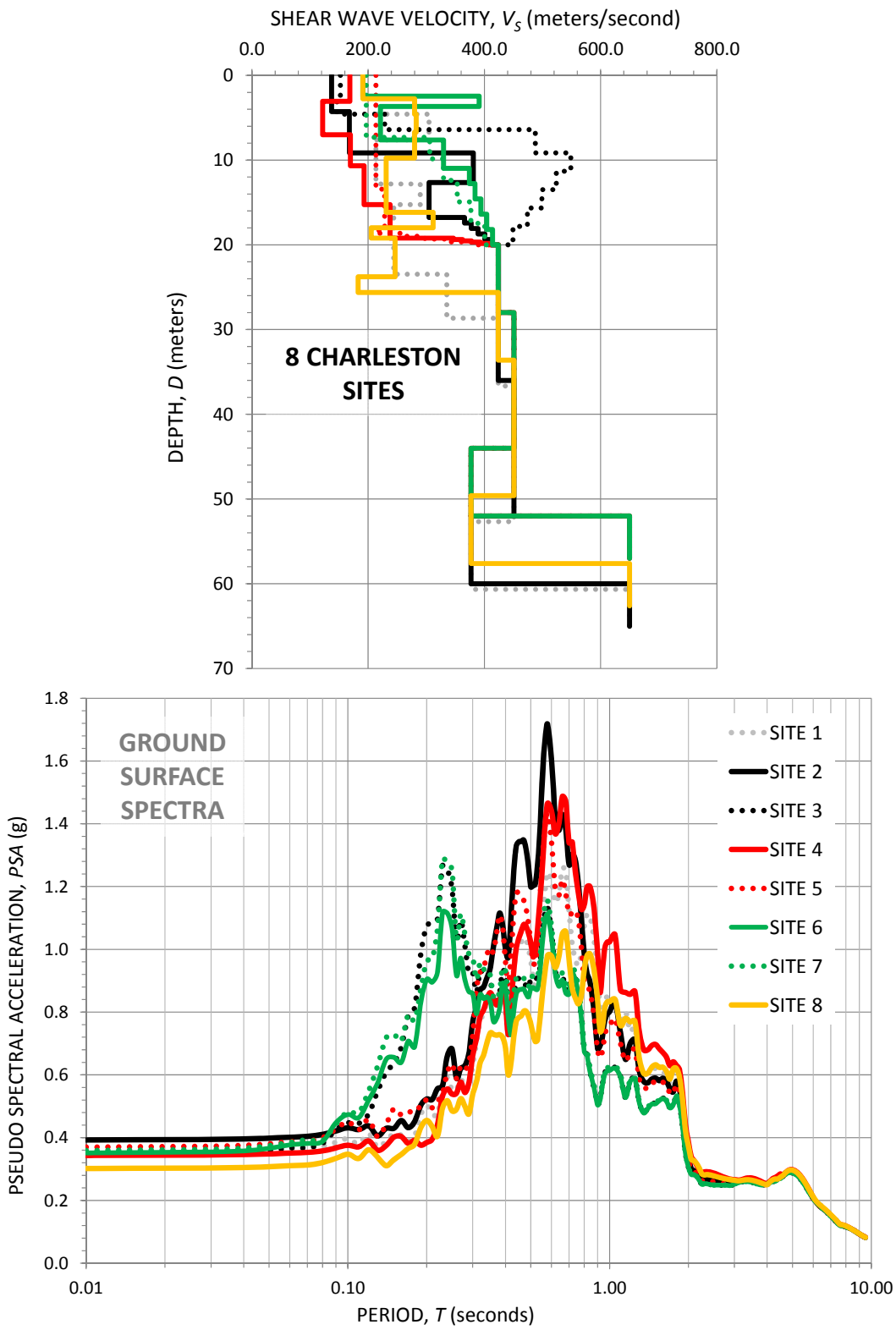

Figure 3-6. Shear wave velocity profiles (top) and ground surface response spectra (bottom) for eight Charleston sites.

Site response analyses using SHAKE were performed for the eight sites using an 800 m sediment stack profile with shear wave velocities ranging from 600 to 800 m/sec and one synthetic hard rock motion input at the bottom of the deep sediment stack. Figure 3-6 (bottom) shows the predicted ground surface spectra for the eight Charleston sites. The response spectra generally show the same response above 2 sec with a plateau of 0.25g peaking to 0.3g at 4 sec at the 1st fundamental period of the deep stack. The scatter in the predicted site response significantly increases below 2 sec where the fundamental periods of the quaternary sediments and the impedance with tertiary sediments from site to site vary substantially.

Ground surface response in Charleston is sensitive to the period content and level of motions that enter the deep stack. Five hard rock motions corresponding to the 1886 Earthquake were used as the high shaking level input motions with average peak ground accelerations, *pga*, of 0.75g. The low and moderate motions were created by simply scaling the *pga* of the 1886 Earthquake to obtain *pga* values of 0.1g and 0.3g, respectively. Figure 3-7 shows the results of site response analysis performed for one Charleston site profile using 15 different rock motions corresponding to low, moderate, and high levels of shaking.

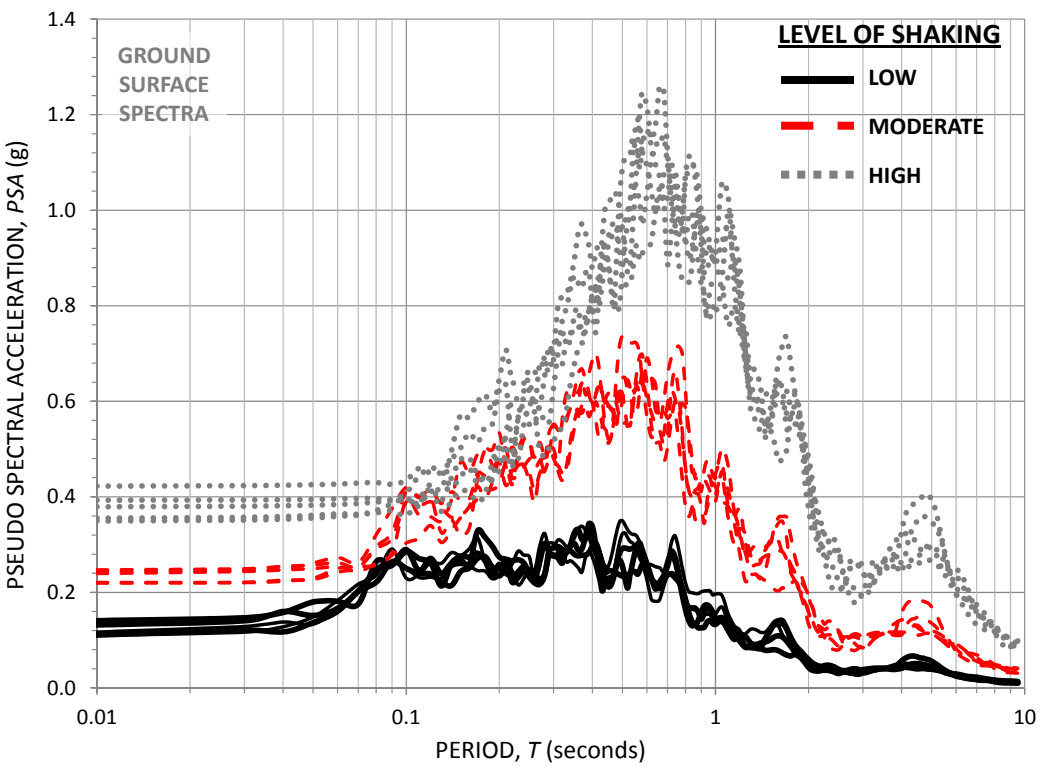

Figure 3-7. Ground surface response spectra from five motions as three different levels of shaking (low, moderate, and high) for one Charleston site profile.

The range of spectral accelerations within each level of shaking indicates that surface response is sensitive to the period content of the hard rock motions. Comparing the spectra across the three levels of shaking shows that amplification or de-amplifcation of the motions and the

corresponding periods of resonance are sensitive to shaking level. The amplification of motions generally shifts to lower periods as the level of shaking decreases; resonance at the fundamental period of the deep sediment stack (4 sec) shows a jump in spectral response at all levels of shaking. This result further highlights the importance of considering multiple earthquake scenarios when predicting surface response due to the uncertainty of earthquake sources and lack of a strong ground motion database in the CEUS.

The preceding site response studies illustrate the potentially wide range in surface response and the importance of identifying three parameters when performing site response analysis in Charleston, South Carolina and other similarly geologic settings in the CEUS: properties of the deep stack, properties of sediments sitting atop the deep stack and period content and level of motions entering the deep stack. Site specific studies of Charleston sites indicate that unique CEUS geologic conditions may not be fully captured by the generalized NEHRP procedures.

Ratios of response spectra from the site specific analysis of the Charleston sites were computed by dividing the ground surface response spectra by 125% of the hard rock spectra or the "B-C Boundary" response. Site response analyses of the eight Charleston sites from Figure 3-6 (top) were performed with five synthetic hard rock motions (M_w 7.3 at an E_D of 123km with average *pga* of 0.75g) representative of 2500-year motions. Figure 3-8 presents the computed ratio of response spectra as a function of period for one class C site (top) and seven class D sites (bottom) including mean (μ) and plus and minus one standard deviation (σ) curves. The NEHRP factors for the short period site amplification factor and mid to long period range site amplification are plotted over the 0.1 to 0.5 sec and 0.4 to 2.0 sec ranges, respectively. NEHRP F_a values for both class C and D sites are generally up to 75% lower than the mean ratios of response spectra computed from the site specific studies, however the equivalent-linear studies are likely unrealistically damping short period motions as shown in Figure 3-5. NEHRP F_v values for both class C and D Charleston sites are generally less than the mean computed ratio of response spectra over the 0.4 to 2.0 sec range; for periods greater than 2.0 sec predicted ratios of response are 2 to 3 times greater than the NEHRP values.

The NEHRP (dashed line) and computed (solid dots with plus and minus one standard deviation lines) site amplification factors are plotted as a function of the average shear wave velocity in the upper 30 m in Figure 3-9. The F_a values (top) show that the mean predicted amplification factors are generally lower than the NEHRP values illustrating that the current models do not capture soil nonlinearity of the deep stack. The F_v values (bottom) from the site specific studies of Charleston sites were computed using the NEHRP 0.4 to 2.0 sec period range (black squares) and 0.4 to 9.5 sec period (red circles). The mean site specific factors computed in the 0.4 to 2.0 sec range are generally 10% to 30% greater than the NEHRP factors for V_{S30} less than 280 m/sec and equal for V_{S30} greater than 280 m/sec. The mean site specific factors computed over the 0.4 to 9.5 sec range, however, exceed NEHRP values by 10% to 30% covering the range of typical Charleston site V_{S30} values. The results presented in Figures 3-8 and 3-9 indicate that the NEHRP site amplification factors do not capture the unique geologic conditions that are found in Charleston. Park and Hashash (2005) present similar findings from site response studies of sites in the Mississippi embayment where deep sediment stacks influence predicted ground surface response.

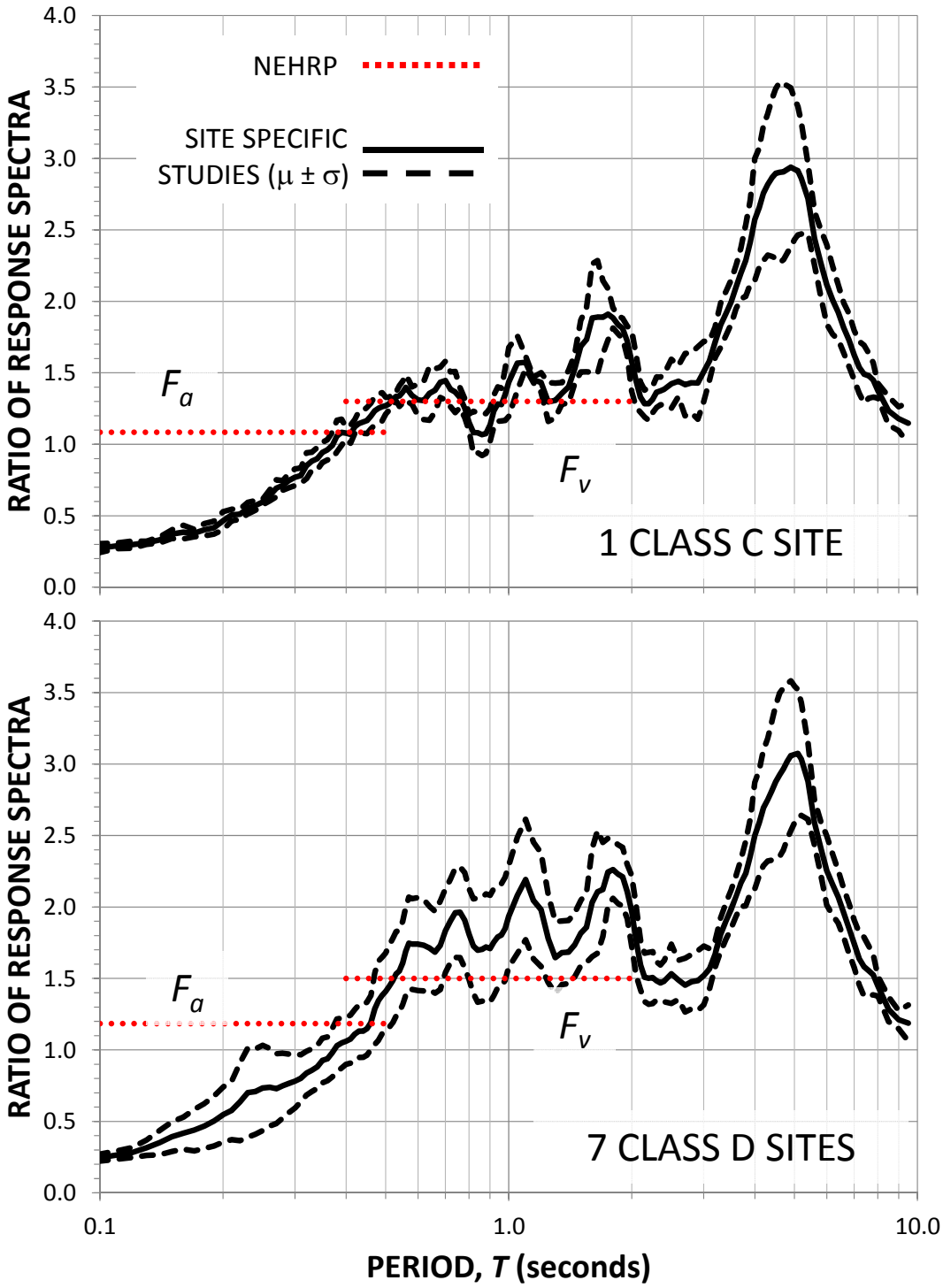

Figure 3-8. Ratio of response spectra computed from site specific studies compared to NEHRP site amplification factors. One class C site (top) and seven class D sites (bottom) from Charleston.

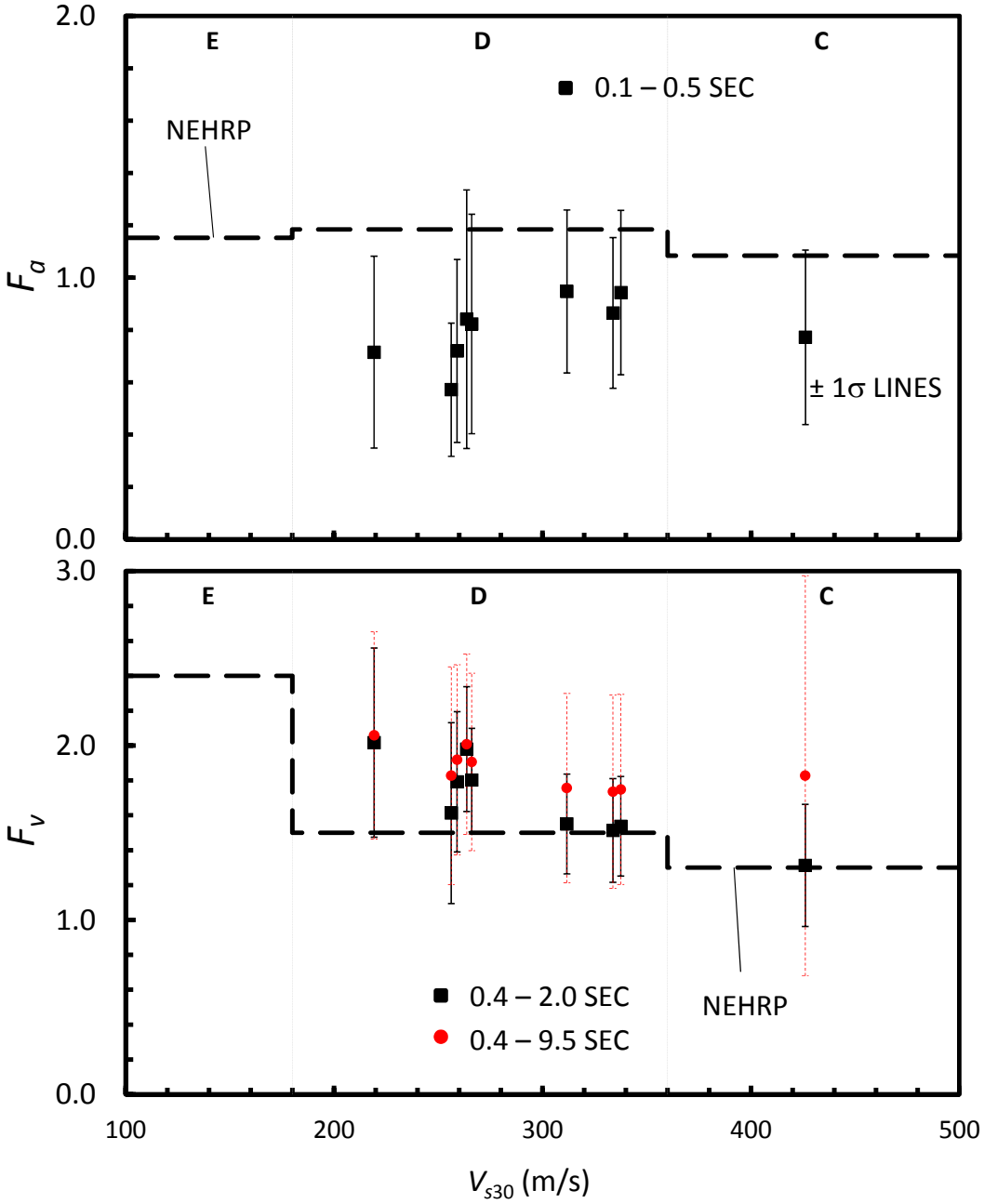

Figure 3-9. Site amplification factors computed from site specific studies of Charleston compared to NEHRP values. The short-period amplification factor, F_a, (top) and the mid-period amplification factor, F_v, (bottom) are shown as a function of V_{s30}.

Mean, minimum, maximum and plus and minus one standard deviation curves computed from the results of the Charleston site specific studies are plotted on Figure 3-10; NEHRP curves (2500-year) for site class C, D, and E are plotted for comparison.

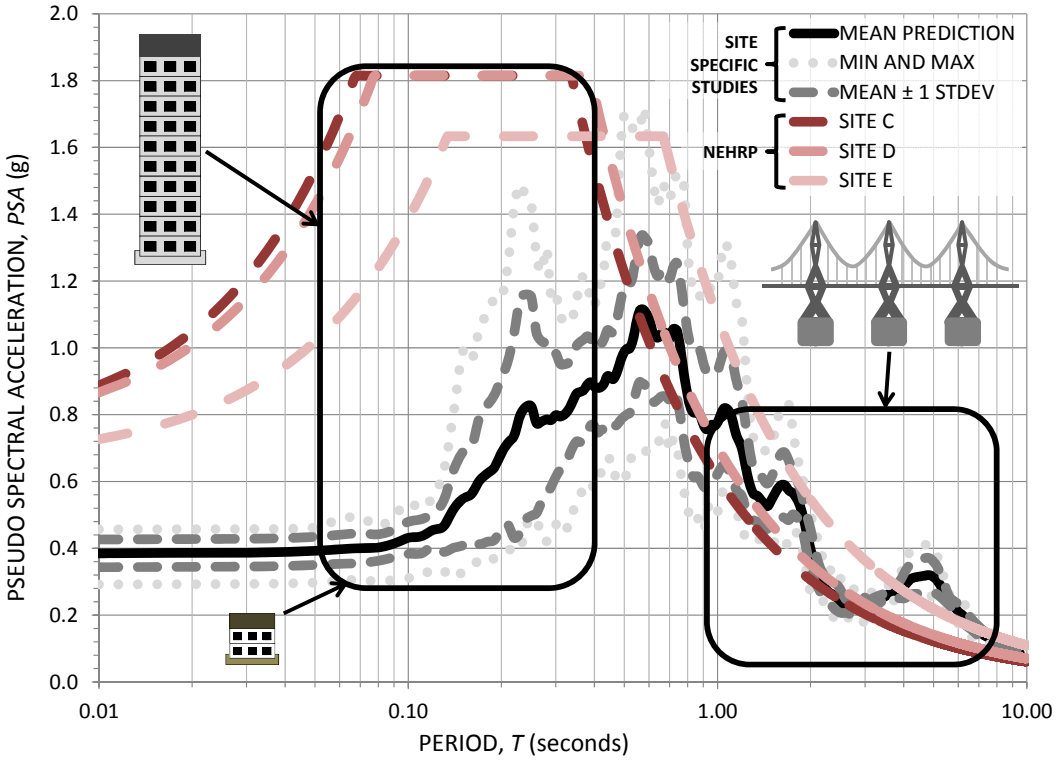

Figure 3-10. Site response spectra computed from site specific studies of Charleston sites compared to NEHRP curves.

The caps in the NEHRP curves are generally centered over a period range shorter than mean predicted response from site specific studies accounting for the deep stack; 0.07 to 0.7 sec versus 0.2 to 1.2 sec, respectively. The mean predicted response for shorter periods up to 1.0 sec are likely higher than shown in Figure 3-10 due to unrealistic over-damping of equivalent-linear computation methods. The mean predicted response for periods greater than 1.0 sec generally exceeds the NEHRP values by 50% at fundamental periods of the deep stack. Higher periods are typically associated with tall, sensitive structures such as bridges, steeples and tall masonry structures. These results further suggest the need to account for unique geologic conditions in the CEUS for developing response spectra to be used for structural design and refinement of the NEHRP procedures. In regions with deep sediment stacks, site response studies and site amplification factors should account for effects of the entire geologic profile from near surface sediments down to hard rock including intermediate impedances between varying geologic strata.

4. SUMMARY AND CONCLUSIONS

Recommendations for seismic design based on typical geotechnical investigations and the NEHRP provisions are biased towards WUS geology and site response behavior. The NEHRP solutions can be misleading because they do not directly account for unique geologic conditions found in the CEUS as illustrated with site specific studies of Columbia and Charleston, South Carolina. Site specific studies directly modeling unique geologic conditions found in Columbia and Charleston illustrate the wide range in site conditions and resulting ground surface response behavior found throughout the CEUS. This study indicates that the NEHRP simplified procedures, specifically the V_{S30}, F_a and F_v parameters do not capture the effects of hard rock close to the ground surface, impedances between geologic layers, and deep sediment stacks. The non-NEHRP site conditions resulting from the unique geologic conditions create challenges and implications for practitioners in the CEUS.

In Columbia, shallow soils sitting atop hard rock found relatively close to the ground surface with a variable weathered profile create impedances often leading to significant amplification of hard rock motions in the 0.1 to 1.0 sec range. In Charleston, shallow quaternary and tertiary soil deposits sitting on the sediment wedge atop hard rock effects ground surface response across a broad range of periods. Accounting for nonlinear soil behavior and the fundamental periods of the deep stack often lead to predictions differing greatly from NEHRP values. When providing seismic recommendations in the CEUS it is important to identify when non-NEHRP site conditions are present and to understand the effects of non-NEHRP site conditions on site response.

In geologic settings similar to Columbia, four important factors influencing ground surface response should be considered:

1. Impedance ratio or ratio of stiffness change between geologic layers

2. Transition of the impedance or rock surface weathering

3. Period content and level of motions entering the impedance

4. Specific site conditions sitting atop the impedance

Predicted ground surface response in Columbia is sensitive to the above factors and commonly leads to predictions greater than NEHRP values. Studies show that stiffer sites have the potential to amplify motions more than softer sites and show that site conditions and site response behavior in Columbia is not captured by the NEHRP procedures.

In geologic settings similar to Charleston three important factors influencing ground surface response should be considered:

1. Properties of the deep sediment stack

2. Properties of sediments sitting atop the deep sediment stack

3. Period content and level of motions entering the deep stack

Predicted ground surface response in Charleston is sensitive to the above factors and commonly leads to predictions less than NEHRP values for shorter periods and greater than NEHRP values for longer periods at the fundamental periods of the sediment wedge and near surface sediments. Studies of Charleston sites show that the unique geologic conditions are not captured by the NEHRP procedures.

Comparing the results of site specific studies from Columbia and Charleston with the isoseismal map of the 1886 Charleston Earthquake illustrates how the combined effects of both unique geologic conditions led to an uptick in damage and perceived shaking near the Fall Line during the historic event. The increase in damage was experienced close to the Fall Line extending approximately 50 km into the Coastal Plain. This observation illustrates how performing site response within the "Wedge Effect" must combine the effects of site response behavior found in both Columbia and Charleston.

Wrong answers produced with NEHRP procedures due to unique CEUS geologic conditions lead to the need for site specific analysis. Lack of seismic experience; lack of a specific set of guidelines for site specific analysis; and difficulty in correctly performing site response analysis leads to less consistency of product in CEUS practice. Region-specific site amplification factors and seismic hazard maps accounting for unique geologic conditions guidelines for performing site specific analysis are needed to steer standard practices in the CEUS away from WUS seismic bias and provide consistency amongst practitioners. CEUS practitioners have the opportunity to highly impact the results of a project depending on the recommended ground surface response. Identifying non-NEHRP site conditions, understanding their effect on ground surface response, and appropriately accounting for the conditions are critical for modifying the current NEHRP provisions and properly designing structures to resist the harmful effects of earthquake shaking in the CEUS.

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